United States Patent [19]

Orth et al.

[11] **4,352,287**

[45] **Oct. 5, 1982**

[54] **ROTATIONAL VISCOMETER**

[75] Inventors: **Heinz W. Orth; James W. Sloot,** both of Calgary, Canada

[73] Assignee: **Dresser Industries, Inc.,** Dallas, Tex.

[21] Appl. No.: **162,137**

[22] Filed: **Jun. 23, 1980**

[51] **Int. Cl.**[3] **G01N 11/14**

[52] **U.S. Cl.** **73/60**

[58] **Field of Search** 73/54, 59, 60

[56] **References Cited**

U.S. PATENT DOCUMENTS

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2,812,656	11/1957	Merrill	73/60
3,602,035	8/1971	Spohn et al.	73/59 X
3,875,791	4/1975	Fitzgerald et al.	73/59
3,977,234	8/1976	Lynch et al.	73/53
4,062,225	12/1977	Murphy, Jr. et al.	73/60
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OTHER PUBLICATIONS

API Recommended Practice, Standard Procedure for Testing Drilling Fluids, Seventh Edition, Apr. 1978.

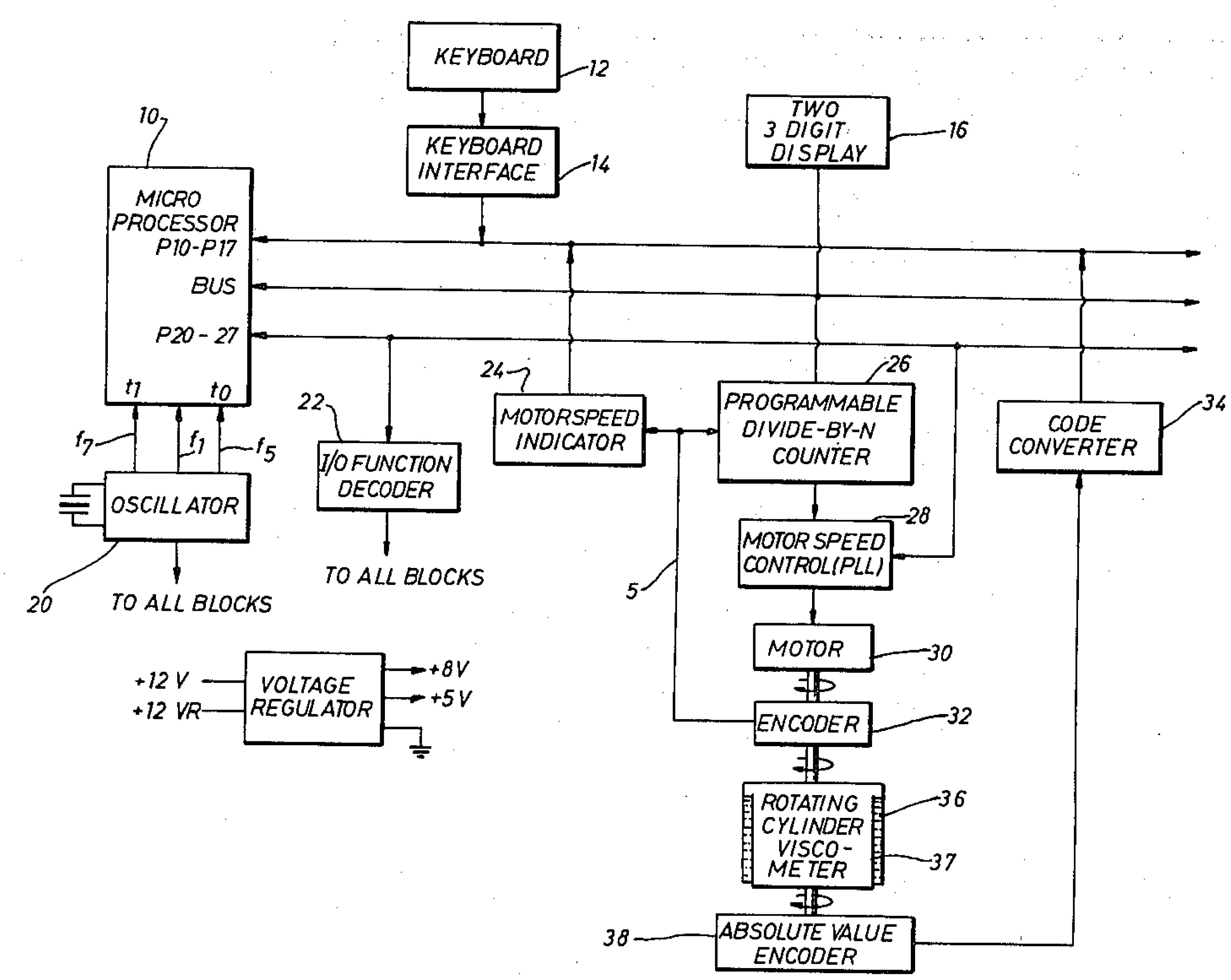
Primary Examiner—James J. Gill

Attorney, Agent, or Firm—John N. Hazelwood; Peggy L. Smith

[57] **ABSTRACT**

A microprocessor controlled rotating-cylinder viscometer for measuring the shear stress at a given shear rate of a fluid is disclosed. The fluid is contained between a rotatable outer cylinder and a rotatable inner cylinder. The inner cylinder rotates in response to the torque produced by rotation of the outer cylinder in the fluid. The amount of rotation of the inner cylinder is related to the shear stress of the fluid. A fast slewing accurate motor speed control is provided for maintaining rotation of the outer cylinder at the selected shear rates. An absolute value shaft encoder monitors the amount of rotation of the inner cylinder to obtain the shear stress readings. The steady state value of the shear stress is obtained by averaging a predetermined number of measurements taken over a sample interval to obtain a stress reading. Consecutive readings are compared until the difference between readings in less than ±1°, the current shear stress then taken on the steady state value.

32 Claims, 16 Drawing Figures



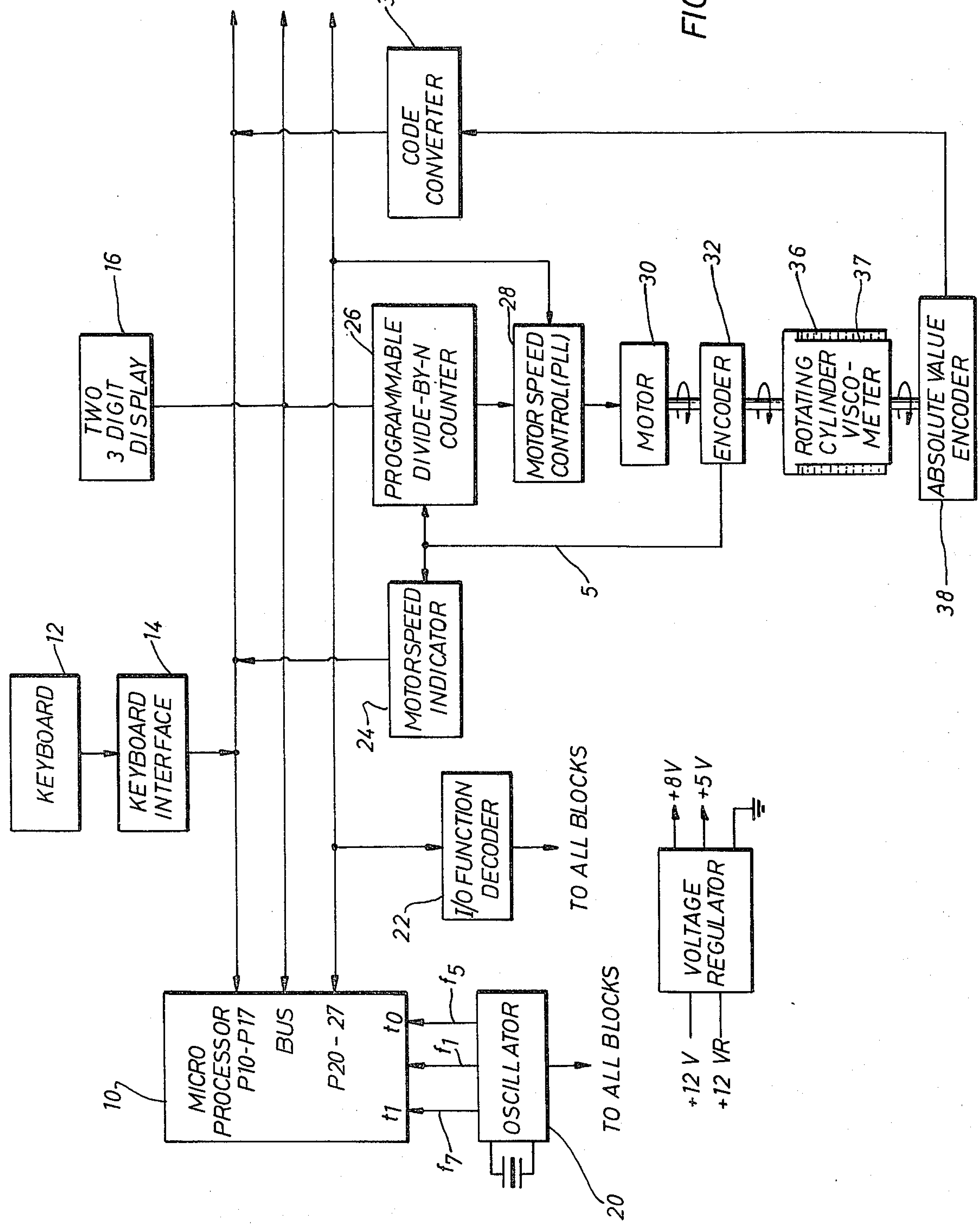

KEYBOARD
KEYBOARD INTERFACE
TWO 3 DIGIT DISPLAY
CODE CONVERTER
PROGRAMMABLE DIVIDE-BY-N COUNTER
MOTOR SPEED CONTROL (PLL)
MOTOR
ENCODER
ROTATING CYLINDER VISCO-METER
ABSOLUTE VALUE ENCODER
MOTORSPEED INDICATOR
I/O FUNCTION DECODER
TO ALL BLOCKS
VOLTAGE REGULATOR
+8V
+5V
+12 V
+12 VR
MICRO PROCESSOR P10-P17
BUS
P20 - 27
t0
t1
OSCILLATOR
TO ALL BLOCKS
f5
f1
f7
10
12
14
16
20
22
24
26
28
30
32
34
36
37
38
5

FIG. 1

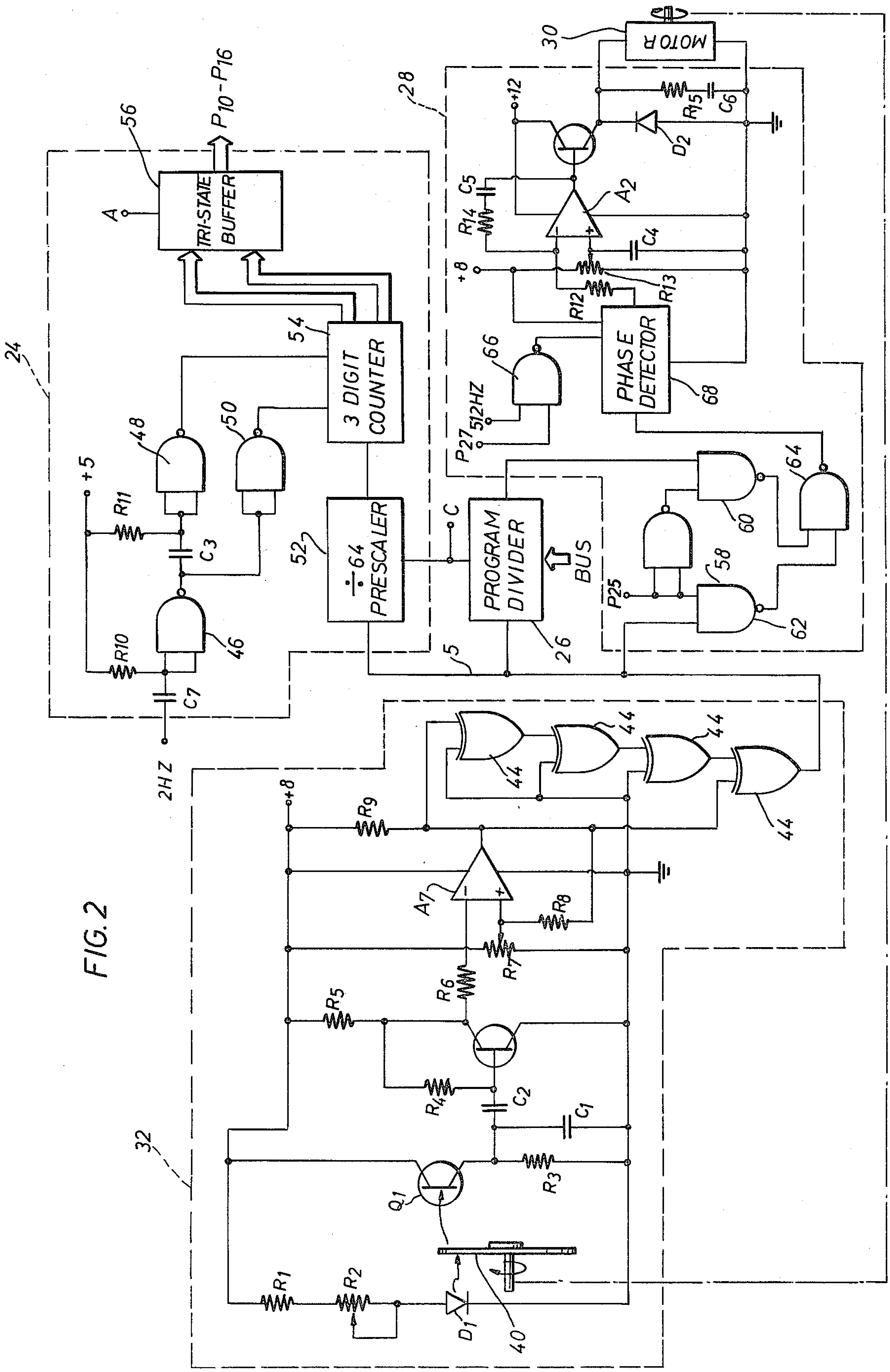
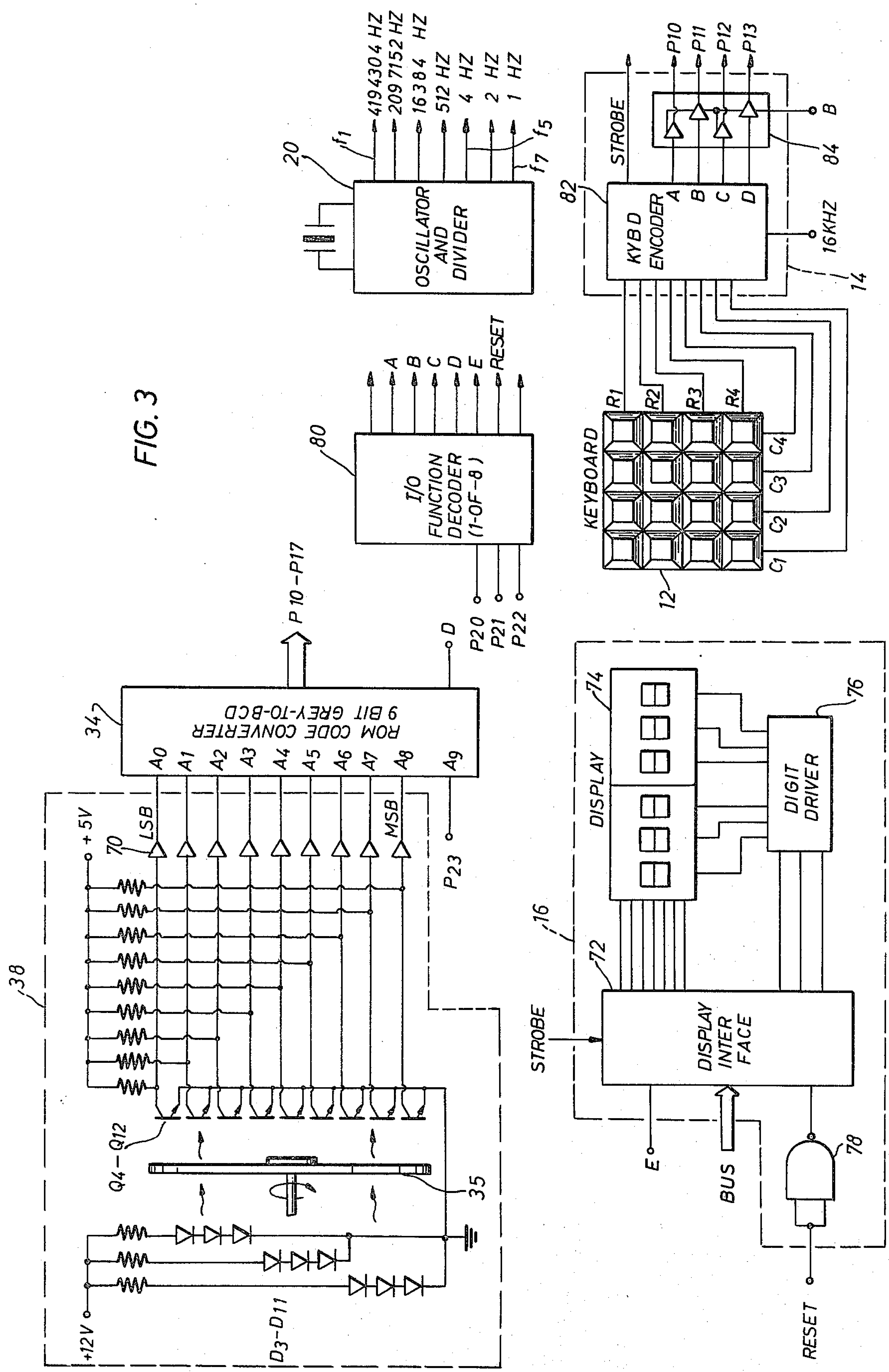

TRI-STATE BUFFER
P10-P16
3 DIGIT COUNTER
÷ 64 PRESCALER
PROGRAM DIVIDER
BUS
PHASE DETECTOR
MOTOR
512HZ
2HZ
+5
+8
+12
A
C
P25
P27
Q1
D1
D2
A2
A7
24
26
28
30
32
40
44
46
48
50
52
54
56
58
60
62
64
66
68

FIG. 2



4194304 HZ
2097152 HZ
16384 HZ
512 HZ
4 HZ
2 HZ
1 HZ
f1
f5
f7
20
OSCILLATOR AND DIVIDER
P10
P11
P12
P13
STROBE
82
84
B
KYBD ENCODER
A
B
C
D
16KHZ
14
I/O FUNCTION DECODER (1-OF-8)
80
A
B
C
D
E
RESET
P20
P21
P22
KEYBOARD
R1
R2
R3
R4
C1
C2
C3
C4
12
P 10 - P17
D
34
ROM CODE CONVERTER
9 BIT GREY-TO-BCD
A0
A1
A2
A3
A4
A5
A6
A7
A8
A9
P23
38
+5V
70
LSB
MSB
Q4 - Q12
35
+12V
D3 - D11
16
72
74
DISPLAY
76
DIGIT DRIVER
STROBE
DISPLAY INTER FACE
E
BUS
78
RESET

FIG. 3

FIG. 4

MEMORY AND I/O ASSIGNMENTS

ROM

ADDRESS	ALLOCATION
000-3CF	PROGRAM MEMORY
3D0-3FF	BCD-7SEG. LOOKUP TABLE
400-7FF	PROGRAM MEMORY

RAM

ADRESS	ALLOCATION
00-07	REGISTERS 0 TO 7
08-17	8 LEVEL STACK
18-1A	KEYBOARD DATA
1B-1D	RPM AND TIME DATA
1E-20	STRESS AND MESSAGE DATA
21-3E	STRESS STORAGE
40-5D	SPEED STORAGE
5E-7F	SCRATCH PAD MEMORY

P1	7	6	5	4	3	2	1	0

P10-13 BCD INPUTS
P14-17 BCD AND DIGIT SELECT INPUTS

P2	7	6	5	4	3	2	1	0

P20-22 CHIP SELECT DECODER ADDRESS
P23-24 CONTROL OUTPUTS
P25 1RPM ACTIVATOR

P27 MOTOR ENABLE ACTIVATOR

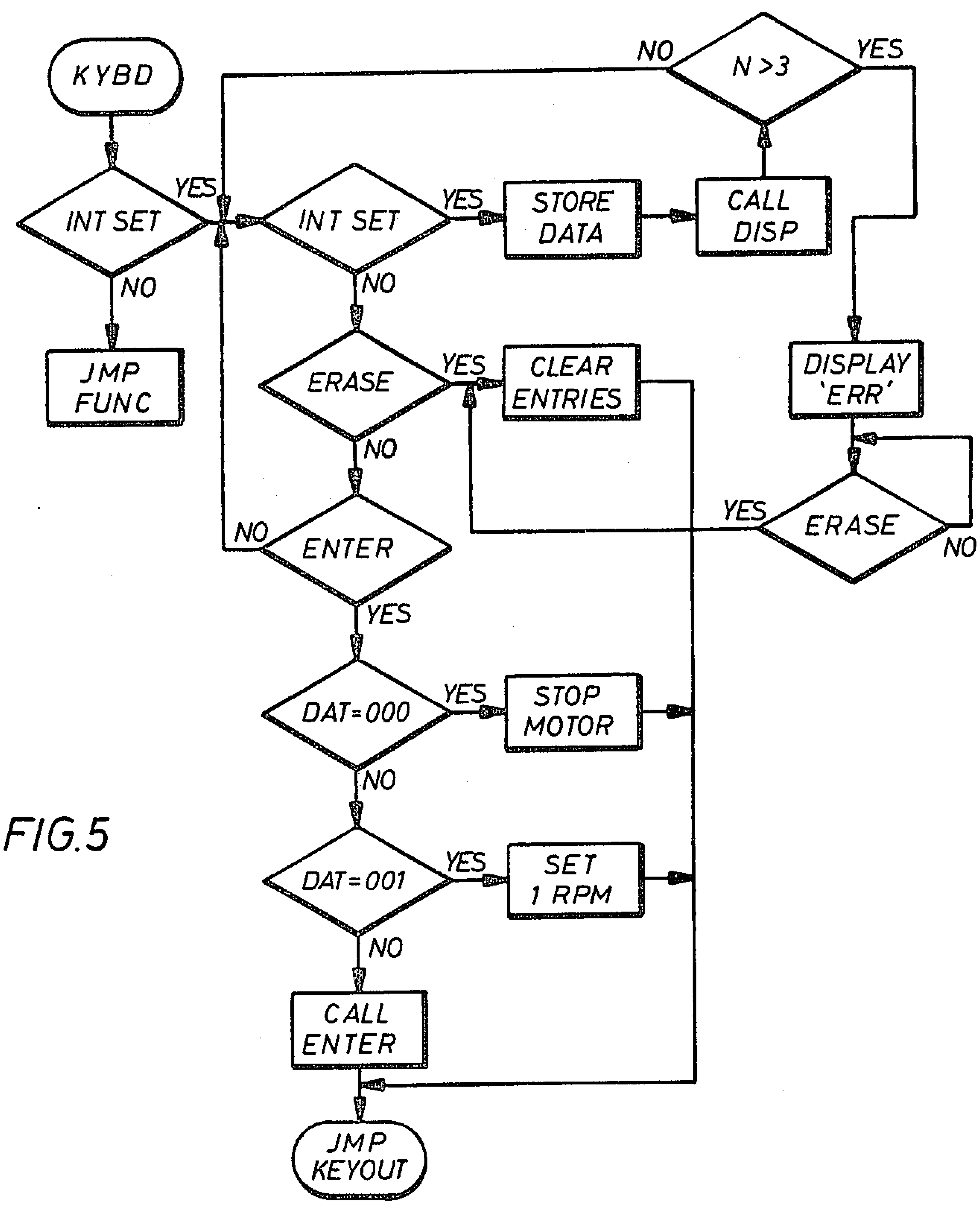

KYBD
INT SET
YES
NO
JMP FUNC
INT SET
YES
NO
STORE DATA
CALL DISP
N >3
NO
YES
DISPLAY 'ERR'
ERASE
YES
NO
CLEAR ENTRIES
ERASE
YES
NO
ENTER
NO
YES
DAT=000
YES
NO
STOP MOTOR
DAT=001
YES
NO
SET 1 RPM
CALL ENTER
JMP KEYOUT

FIG.5

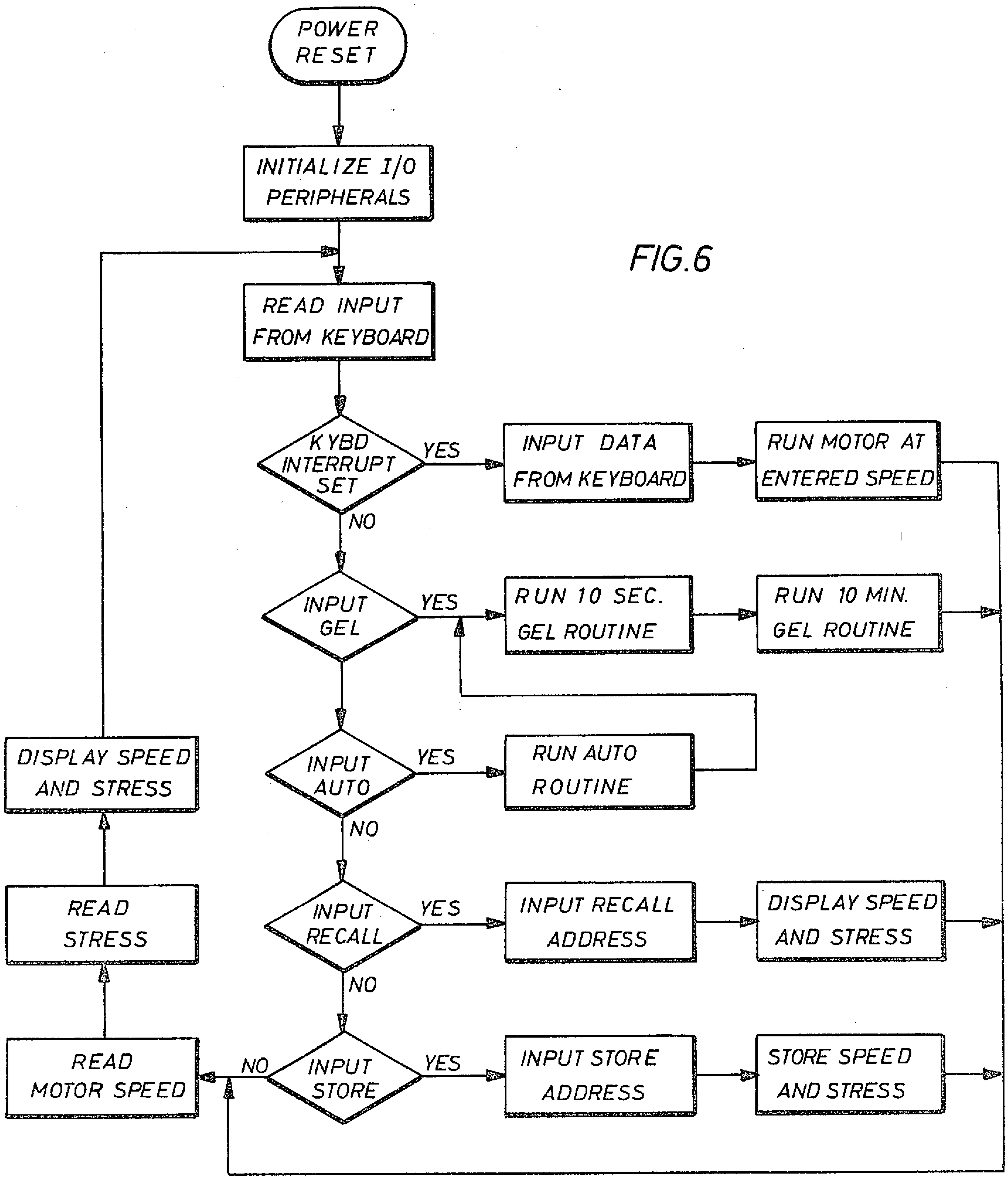
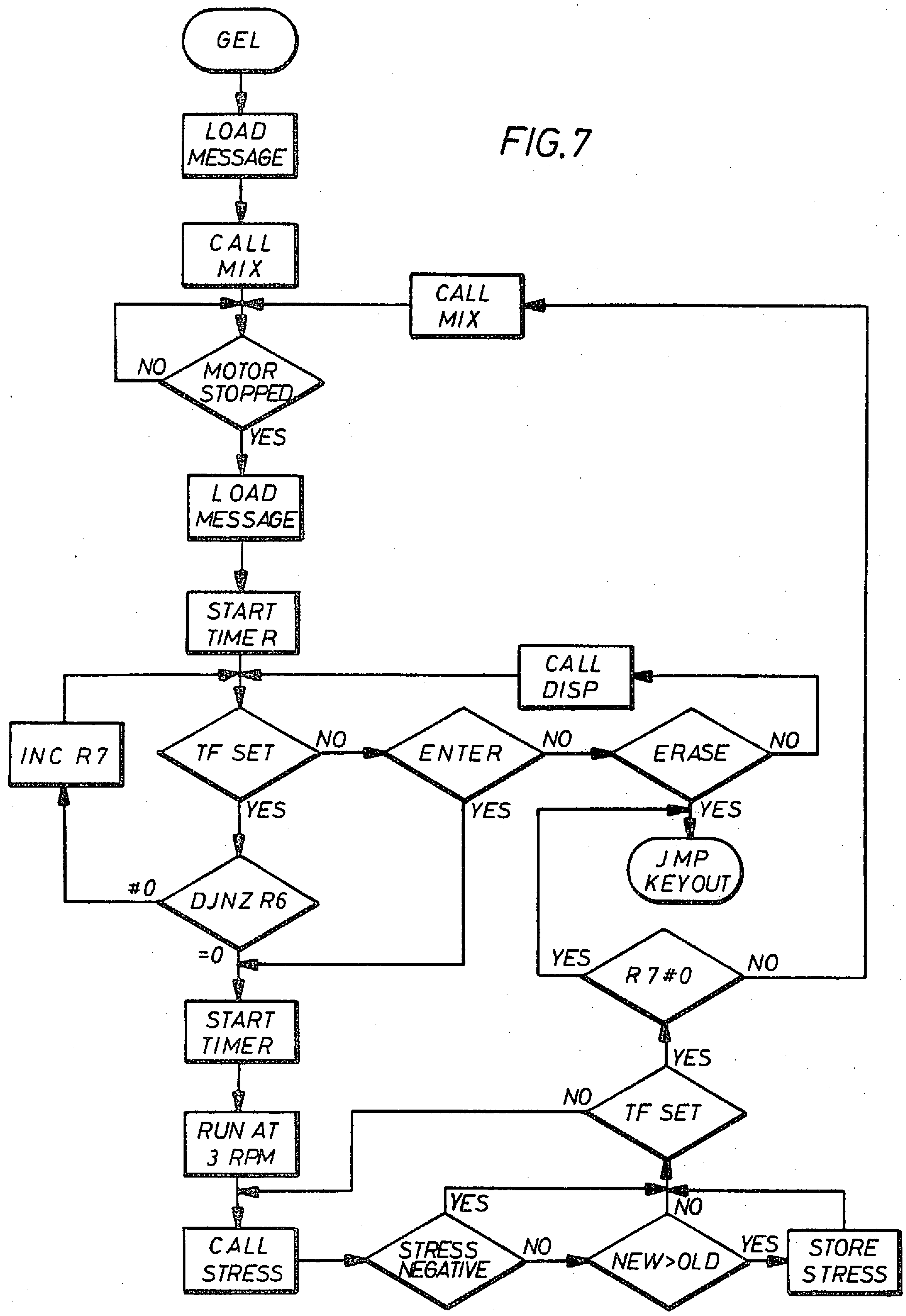

POWER RESET
INITIALIZE I/O PERIPHERALS
READ INPUT FROM KEYBOARD
KYBD INTERRUPT SET
YES
NO
INPUT DATA FROM KEYBOARD
RUN MOTOR AT ENTERED SPEED
INPUT GEL
YES
RUN 10 SEC. GEL ROUTINE
RUN 10 MIN. GEL ROUTINE
INPUT AUTO
YES
NO
RUN AUTO ROUTINE
DISPLAY SPEED AND STRESS
INPUT RECALL
YES
NO
INPUT RECALL ADDRESS
DISPLAY SPEED AND STRESS
READ STRESS
READ MOTOR SPEED
NO
INPUT STORE
YES
INPUT STORE ADDRESS
STORE SPEED AND STRESS

FIG.6



GEL
LOAD MESSAGE
CALL MIX
CALL MIX
NO
MOTOR STOPPED
YES
LOAD MESSAGE
START TIMER
CALL DISP
INC R7
TF SET
NO
ENTER
NO
ERASE
NO
YES
YES
YES
JMP KEYOUT
#0
DJNZ R6
=0
YES
R7#0
NO
START TIMER
YES
NO
TF SET
RUN AT 3 RPM
YES
NO
CALL STRESS
STRESS NEGATIVE
NO
NEW>OLD
YES
STORE STRESS

FIG. 7

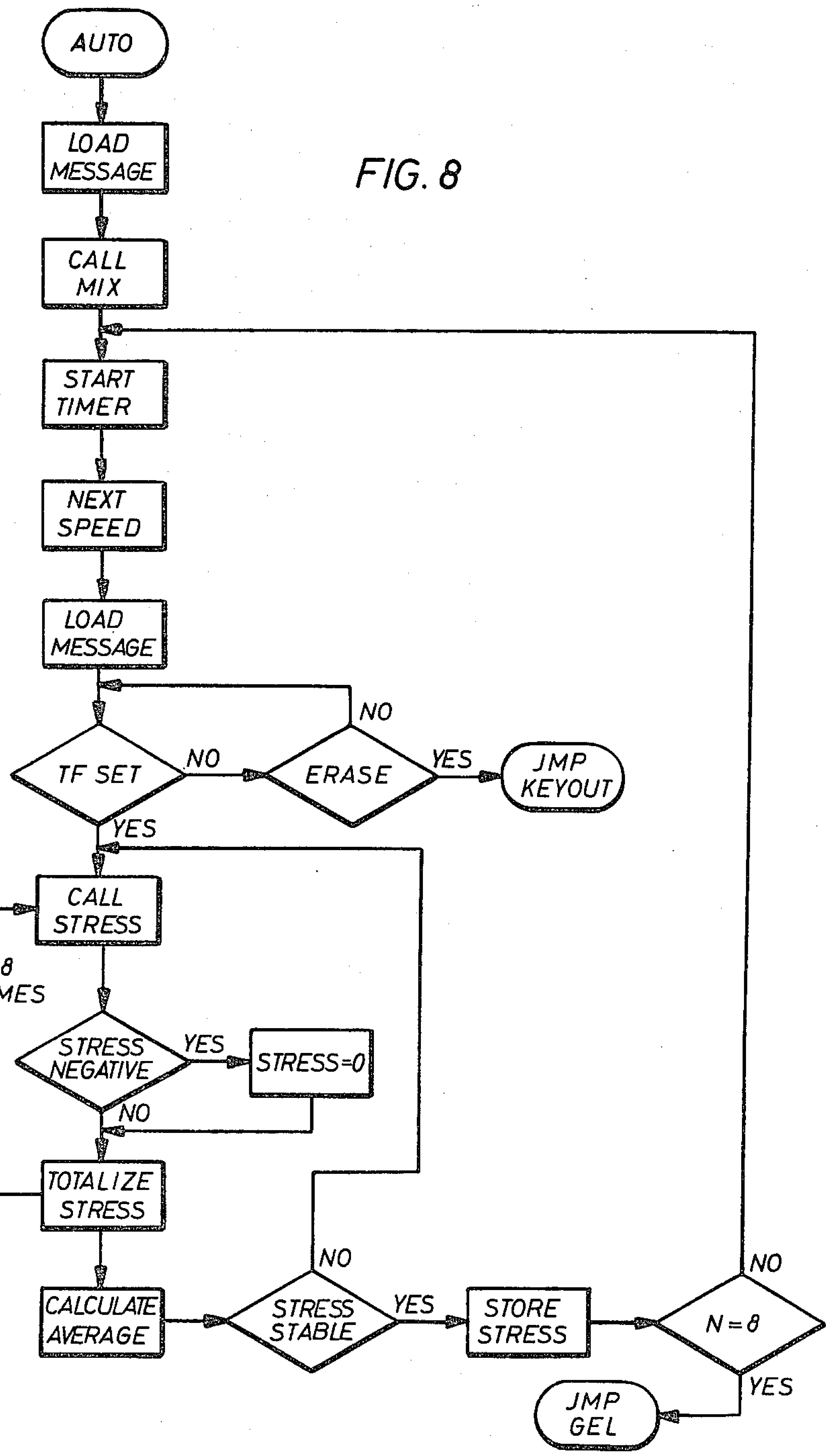

AUTO
LOAD MESSAGE
CALL MIX
START TIMER
NEXT SPEED
LOAD MESSAGE
TF SET
NO
ERASE
NO
YES
JMP KEYOUT
YES
CALL STRESS
128 TIMES
STRESS NEGATIVE
YES
STRESS=0
NO
TOTALIZE STRESS
CALCULATE AVERAGE
STRESS STABLE
NO
YES
STORE STRESS
N=8
NO
YES
JMP GEL

FIG. 8

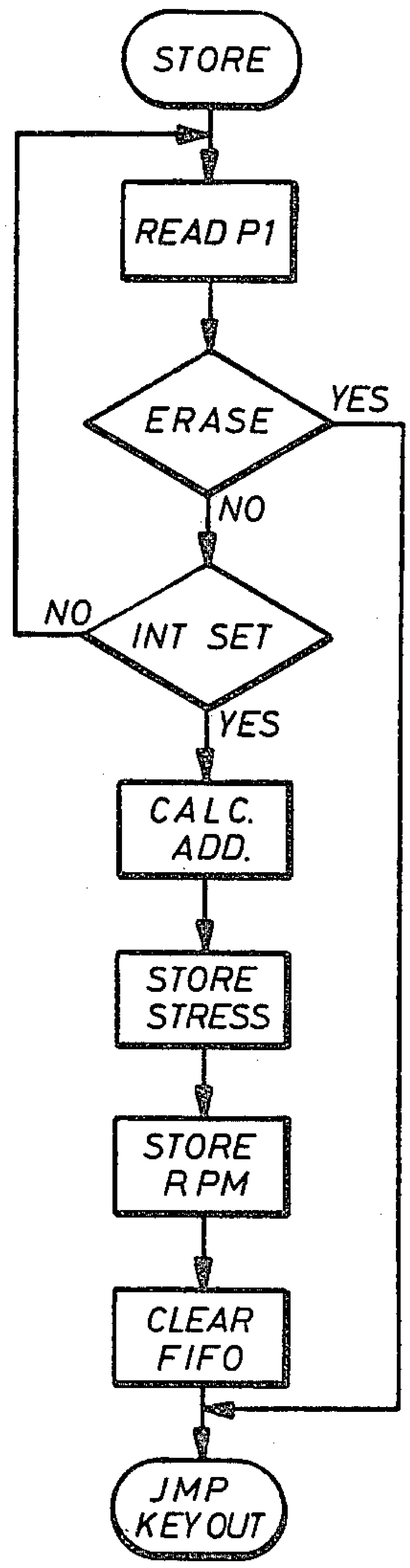

STORE
READ P1
ERASE
YES
NO
NO
INT SET
YES
CALC. ADD.
STORE STRESS
STORE RPM
CLEAR FIFO
JMP KEY OUT

FIG. 9

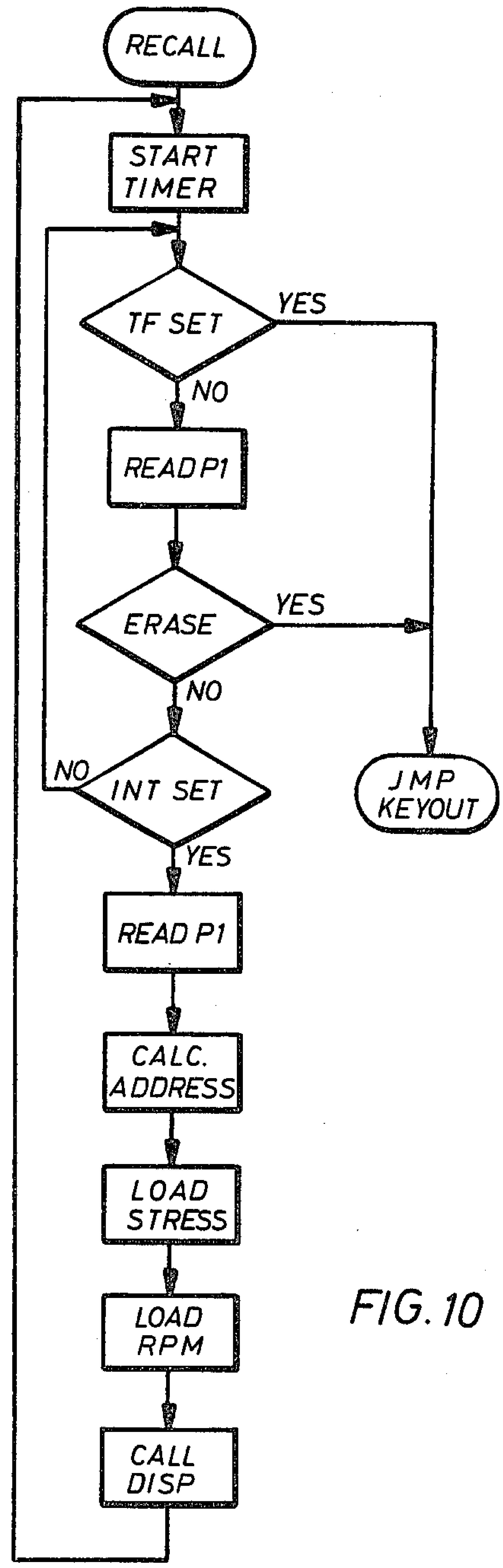

RECALL
START TIMER
TF SET
YES
NO
READ P1
ERASE
YES
NO
NO
INT SET
YES
JMP KEYOUT
READ P1
CALC. ADDRESS
LOAD STRESS
LOAD RPM
CALL DISP

FIG. 10

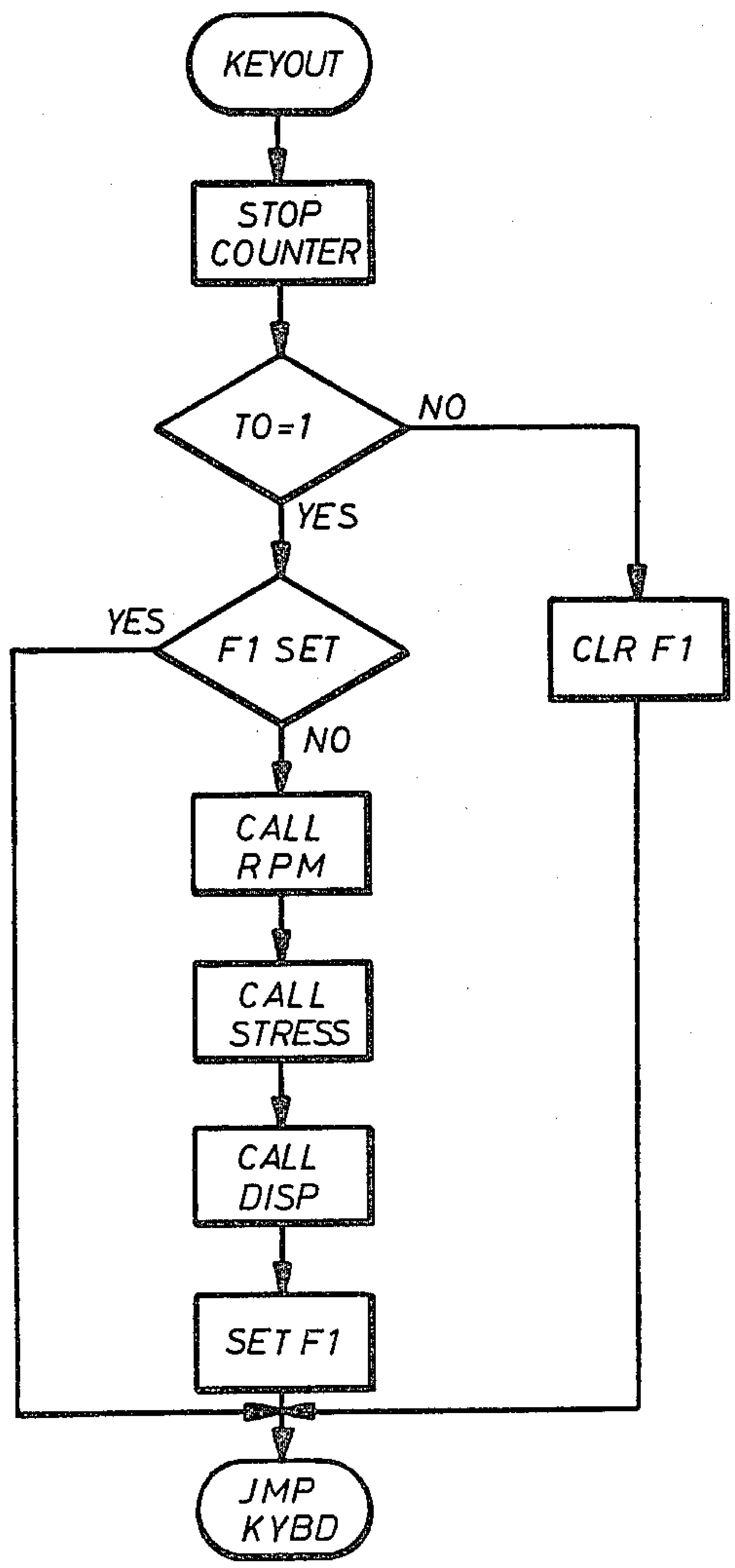

KEYOUT
STOP COUNTER
TO=1
NO
YES
F1 SET
YES
NO
CLR F1
CALL RPM
CALL STRESS
CALL DISP
SET F1
JMP KYBD

FIG. 11

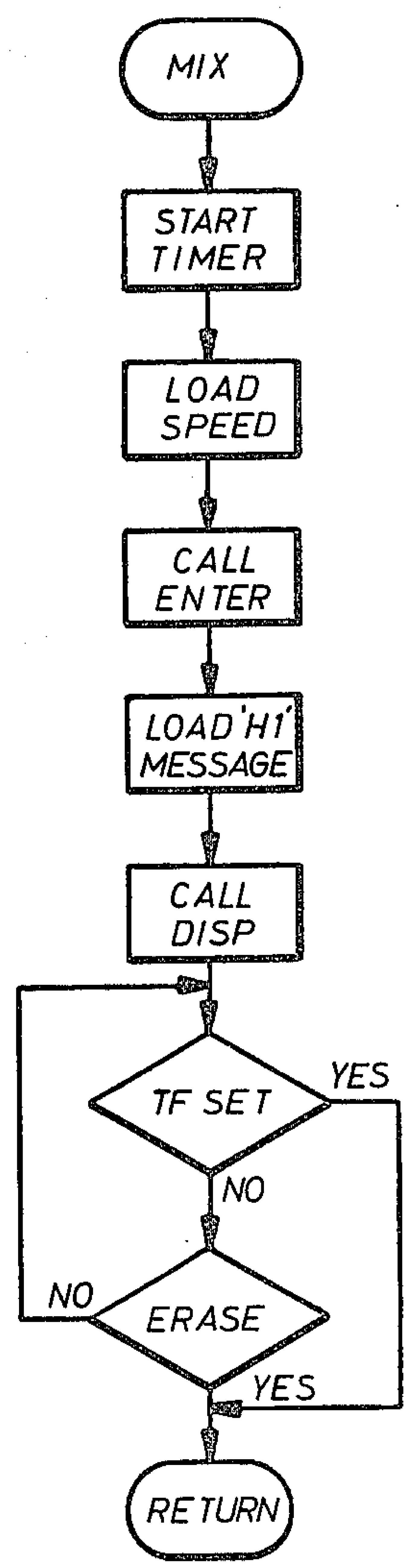

MIX
START TIMER
LOAD SPEED
CALL ENTER
LOAD 'H1' MESSAGE
CALL DISP
TF SET
YES
NO
ERASE
NO
YES
RETURN

FIG. 12

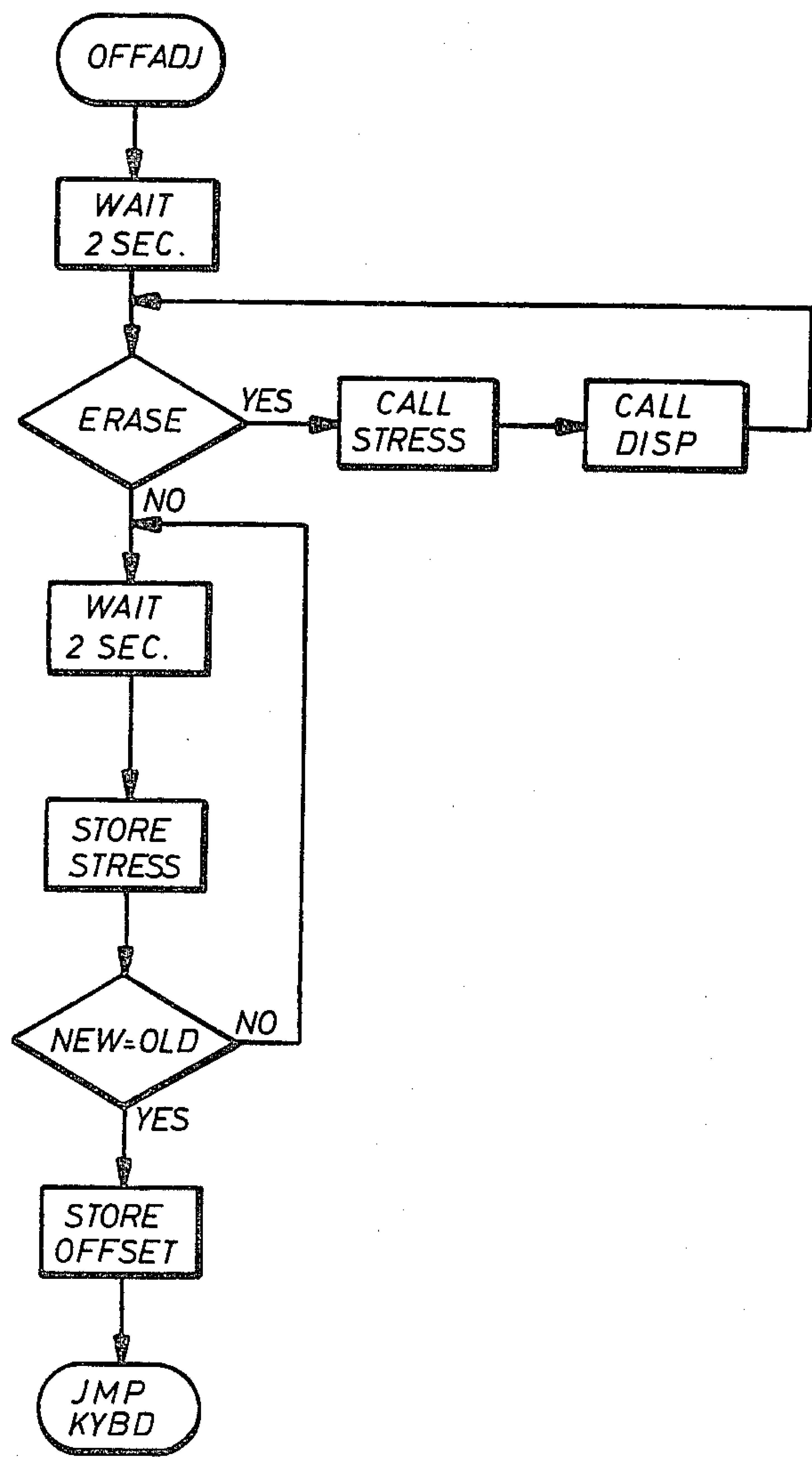

OFFADJ
WAIT 2 SEC.
ERASE
YES
CALL STRESS
CALL DISP
NO
WAIT 2 SEC.
STORE STRESS
NEW=OLD
NO
YES
STORE OFFSET
JMP KYBD

FIG.13

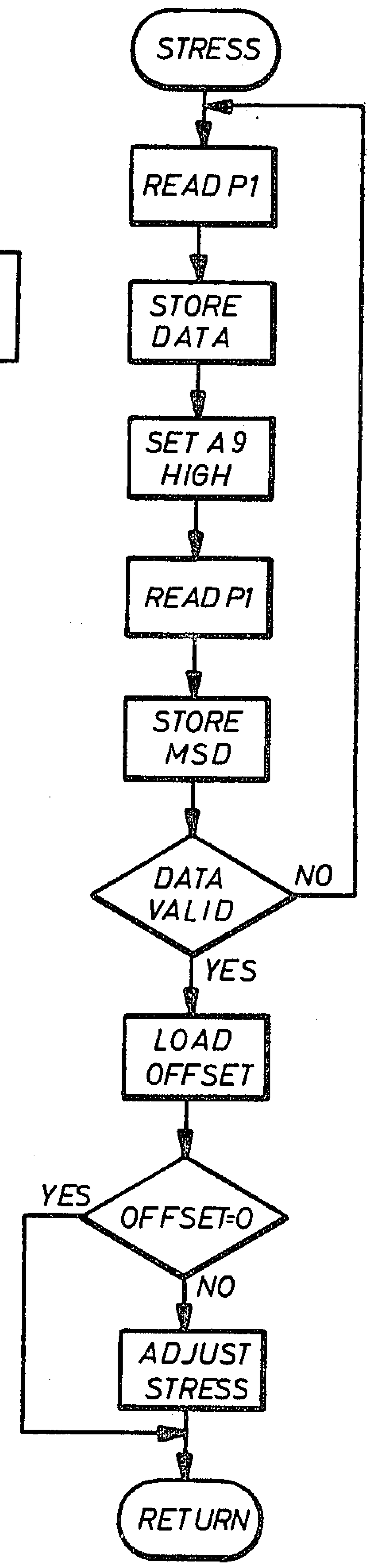

STRESS
READ P1
STORE DATA
SET A9 HIGH
READ P1
STORE MSD
DATA VALID
NO
YES
LOAD OFFSET
OFFSET=0
YES
NO
ADJUST STRESS
RETURN

FIG.14

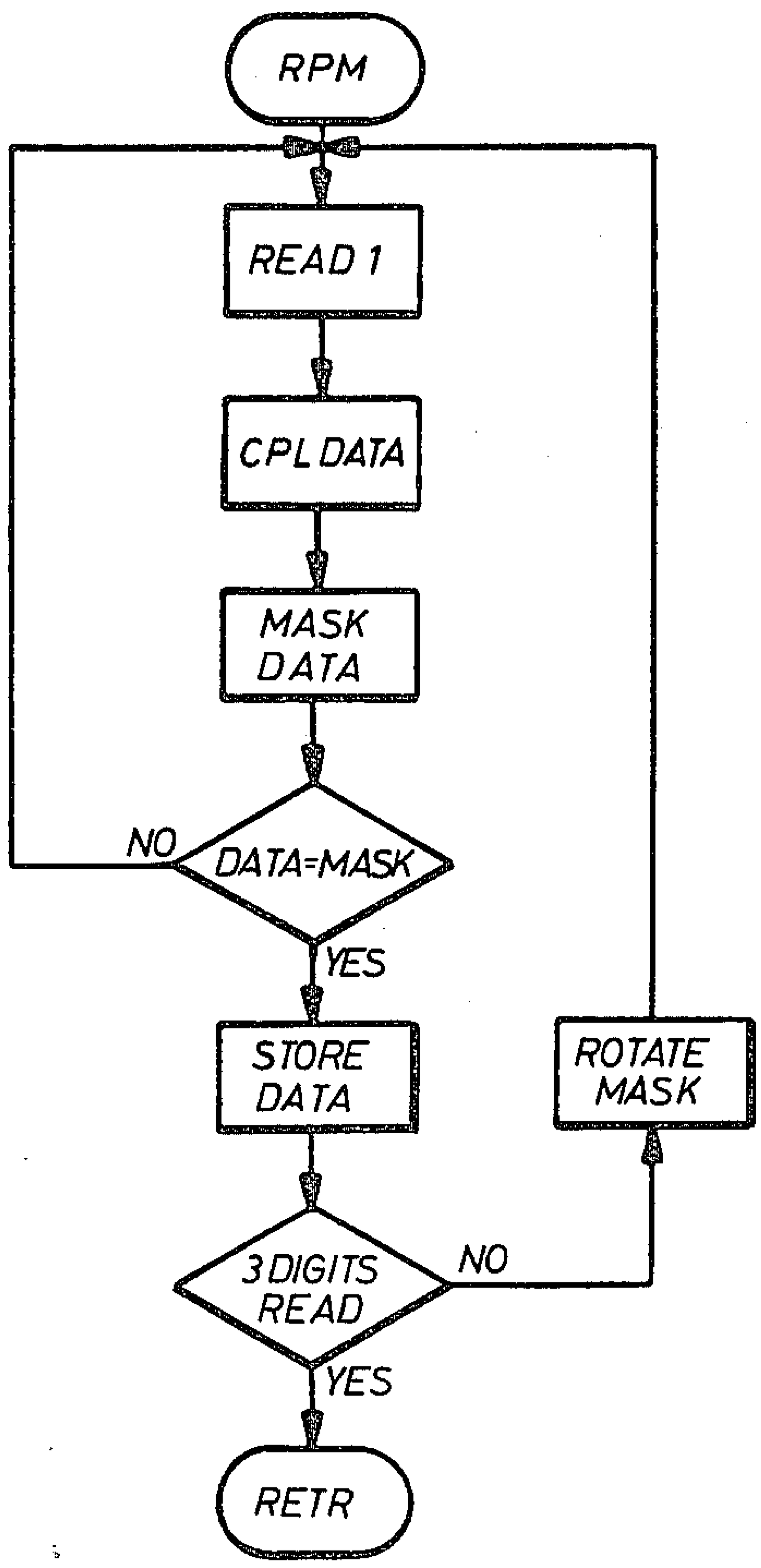

RPM
READ 1
CPL DATA
MASK DATA
NO
DATA=MASK
YES
STORE DATA
ROTATE MASK
3 DIGITS READ
NO
YES
RETR

FIG.15

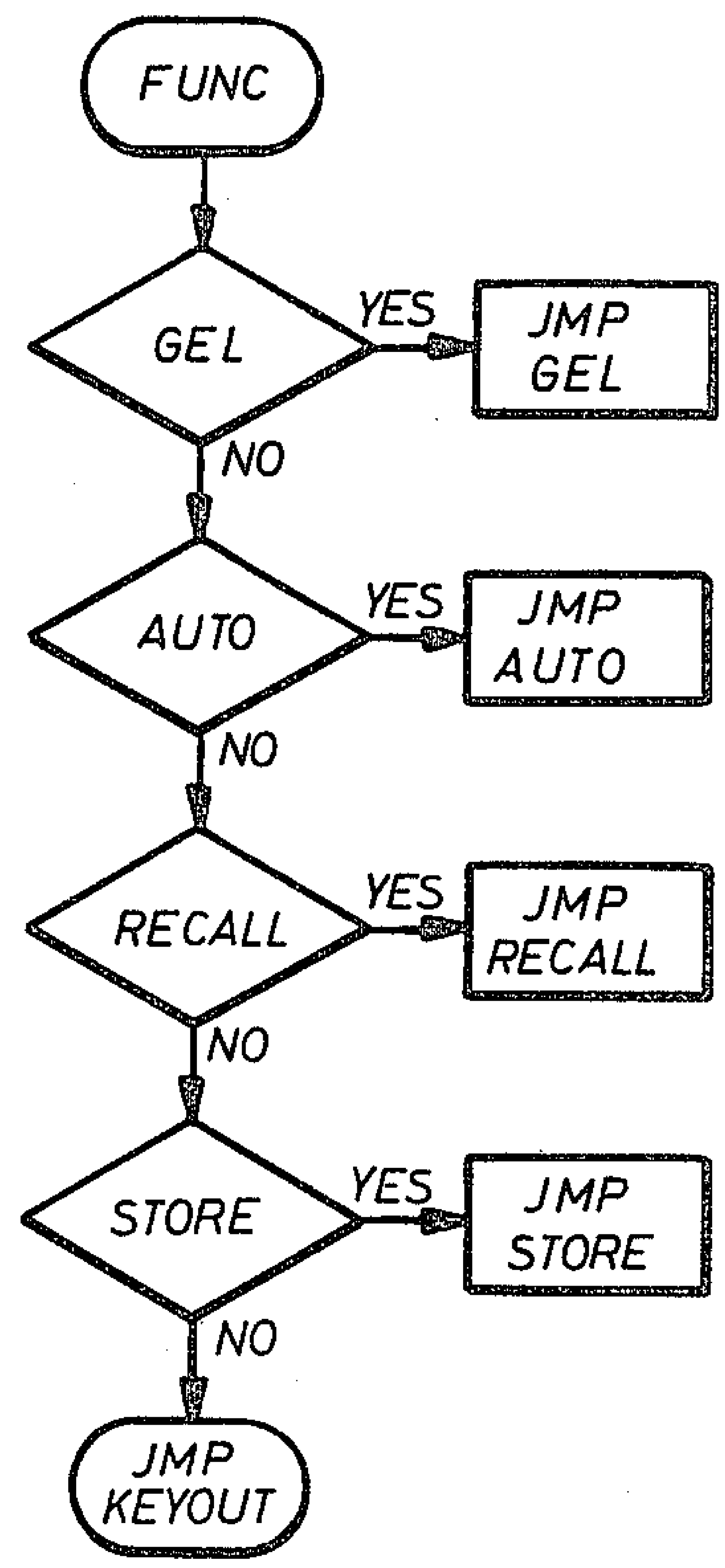

FUNC
GEL
YES
JMP GEL
NO
AUTO
YES
JMP AUTO
NO
RECALL
YES
JMP RECALL
NO
STORE
YES
JMP STORE
NO
JMP KEYOUT

FIG.16

ROTATIONAL VISCOMETER

BACKGROUND OF THE INVENTION

This invention relates to rotational viscometers for measuring rheometric properties of a fluid. More particularly, this invention relates to a microprocessor controlled rotational type viscometer for automatically and accurately obtaining the steady state shear stress of a fluid at various preselected shear rates.

Properties of fluids, such as the shear stress, shear strength, yield stress, plastic viscosity, etc., are important in many different industries. For example, viscometers are widely used in the drilling industry to measure these properties of drilling fluids that are used to drill oil and gas wells. Information obtained with viscometers is important in controlling the effectiveness of the drilling fluid in, (1) removal of cuttings from the bottom of the hole and carrying them to the surface, (2) holding the cuttings and weight material in suspension when circulation is interrupted, (3) releasing the cuttings and any entrained gases at the surface, (4) transmission of hydraulic horsepower to the drill bit, (5) minimizing annular pressure drops so as to avoid fracturing and the resulting loss of circulation in the uncased hole, (6) maximizing bore hole stability by controlling erosional effects on the well bore while circulating, and (7) reducing to a minimum any adverse effects upon the formation adjacent to the bore hole.

Direct-indicating concentric cylinder rotational viscometers powered by means of an electric motor or hand crank have found wide acceptance in the petroleum industry as an acceptable approach to measuring the viscocity of drilling fluid. In such a viscometer, the drilling mud is contained in the annular space between two cylinders. The outer cylinder or rotor sleeve is driven at a constant rotational velocity or shear rate. Located within the outer cylinder is an inner cylinder. The rotation of the outer cylinder in the mud produces a torque on the inner cylinder. A torsion spring restrains rotational movement of the inner cylinder. A dial scale is attached to the inner cylinder, and with rotation of the inner cylinder, indicates on a fixed pointer the angular displacement of the inner cylinder. The torque produced on the inner cylinder by rotation of the outer cylinder rotates the inner cylinder until the torque on the torsional spring is counter balancing the torque exerted by the fluid. At this point, a reading of the viscosity of the fluid may be taken.

However, direct-indicating rotational viscometers suffer from several problems. Primarily, a high degree of accuracy in shear stress readings is difficult to attain when reading from a scale. Fluctuations in the meter scale about an average position occur as a result of changing physical properties of the fluid and the presence of solid particles in the fluid as the outer cylinder is rotated. As a result, the operator reading the scale must interpolate the average position of the scale. The API recommendation Standard Procedure for Testing Drilling Fluids (APIRP 13B, 7th Edition, April 1978) suggest a that before reading the shear stress at a given shear rate, the dial reading should be allowed to come to a "steady value." Heretofore, rotational viscometers had to depend upon the operator's subjective determination of when a "steady value" has been attained. However, a slow drift in the steady dial reading may occur even with relatively stable readings on the dial, i.e. there are relatively small fluctuations in the dial's position. This drift can be brought about by gradual change in the structure of the fluid. As a result, a quantitative determination of when a steady value or steady state condition of the fluid had been reached is difficult to attain in these prior-art-viscometers.

A further problem in direct-indicating rotational viscometers is the inability of the outer cylinder to change speeds quickly, and at the same time, be capable of maintaining accurate selected shear rate speeds. One such prior-art means for maintaining an accurate shear rate speed in a rotational viscometer is disclosed in U.S. Pat. No. 4,062,225. A phase locked loop (PLL) motor speed control circuit is shown for controlling the shear rate speed of the rotated outer cylinder. Attached to the motor shaft is a high inertia flywheel which functions to dampen out speed variations of the motor at the selected shear rates. Unfortunately, the inertia of the flywheel does not permit a rapid change in the motor speed as the shear rate is changed.

This inability to rapidly change speed becomes especially significant when the viscometer is measuring the "Gel" strength of the fluid. As recommended at Page 6 of the API bulletin identified above, when measuring "Gel" strength, the fluid is mixed at high speed for 10 seconds, stopped for 10 seconds and then run at 3 RPM. The maximum reading is recorded and process of mixing, stopping and running at a low RPM is repeated. For this procedure, it is implied that following the mixing step, the outer cylinder is immediately stopped to allow the fluid to reform. This would not be possible with a motor speed control system utilizing a flywheel to attain high accuracy shear rate control. The inertia of the flywheel requires a significant amount of time for the rotating outer cylinder to come to a stop.

Accordingly, it would be advantageous to provide a rotating type viscometer in which the shear rate speeds can be controlled to a high degree of accuracy, but at the same time, permit rapid changes in the rotation of the outer cylinder. It would also be advantageous to provide a viscometer that could determine quantitatively the steady state condition of the shear stress at each selected shear rate to achieve a high degree of accuracy in shear rate measurements. It would also be advantageous to provide a viscometer that could automatically and accurately measure the shear stress of a fluid at each of a pre-selected number of shear rates to obtain data values which will permit the piece-wise linear approximation to the shear stress profile of the fluid, particularly in the region of actual shear rate conditions encountered in the annulus of a well bore.

SUMMARY OF THE INVENTION

In accordance with this invention, a rotational concentric cylinder viscometer for measuring the steady state shear stress of a fluid at a given shear rate is provided. The fluid, whose viscosity is to be measured, is contained between a rotatable outer cylinder and a spring loaded rotatable inner cylinder such that rotation of the outer cylinder produces a torque acting through the fluid on the inner cylinder thereby causing the inner cylinder to rotate. The total amount of rotation of the inner cylinder is related to the shear stress of the fluid as measured at the shear rate.

A microprocessor unit is provided to input and output data signals that will select the various shear rates of rotation of the outer cylinder, and measure the resulting amount of rotation of the inner cylinder at each selected shear rate. A system clock provides several system clock signals to control the various functions and timing of the viscometer. A shear rate controller responds to the system clock and the shear rate selecting data from the microprocessor to rotate the outer cylinder at the selected constant angular velocity. An angular position indicator comprising an absolute value shaft encoder outputs a digital Gray code that is used to indicate the angular position of the inner cylinder.

A function selector means comprising a manually actuated keyboard is connected to the microprocessor input data lines for inputting both the mode of operation of the microprocessor and for inputting the various pre-selected shear rates at which the outer cylinder is to be rotated. A display means is provided to display both a measured shear stress and the angular velocity of the outer cylinder at which the display shear stress was measured.

The shear rate controller that controls the rate of rotation of the outer cylinder includes a programmable frequency divider that responds to the shear rate selecting data from the microprocessor to produce a phase detector clock signal. The phase detector clock signal is produced by dividing the feedback frequency signal obtained from a speed encoder connected to the outer cylinder. The speed encoder is an optical incremental encoder mechanically connected to the outer cylinder for rotation therewith. A motor drive means responds to the phase detector clock signal to generate the excitation signal to the motor that rotates the outer cylinder. This motor drive means includes a phase detector that responds to the system clock and the phase detector clock signal to generate a phase error signal that indicates the phase difference between the phase detector clock signal and a reference signal. Also included is an amplifier that filters and amplifies the phase error signal to produce the motor excitation signal. The motor used to rotate the outer cylinder is a DC-motor of the ironless armature type.

In another aspect of the invention, a method for obtaining the steady state shear stress of a fluid at a selected shear rate using the microprocessor controlled rotating-cylinder viscometer is also disclosed. The method comprises the steps of changing the outer cylinder rotational speed to a selected shear rate, determining a current average value for the angular position of the inner cylinder from a predetermined number of position measurements taken at a predetermined sample rate. The difference between a current average value and the last obtained average value is then obtained. The result is then compared with a predetermined number of degrees to determine if the steady state condition of shear stress has been attained. If not, the process of obtaining a current average value is repeated until the difference is less than or equal to the predetermined number of degrees, at which point the current average value is taken as the steady state shear stress.

In another aspect of the invention, a method for obtaining the instant "GEL" and 10 minute "GEL" using the microprocessor controlled rotating cylinder viscometer is also disclosed. The method comprises the programmed steps of mixing, waiting the appropriate delay time, and starting the outer cylinder at 3 RPM during which the highest shear stress reading obtained in an interval of 20 seconds, corresponding to one complete revolution of the outer cylinder, is stored for later recall.

In yet a further aspect of the invention, a method for obtaining the shear stress profile (shear stress vs. shear rate) of a fluid using the microprocessor controlled rotating-cylinder viscometer is disclosed. The method for determining the steady state shear stress at a selected shear rate is repeated for each of the pre-selected shear rates until all readings have been obtained.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of this invention are set forth in the appended claims. The invention and advantages thereof may best be understood by reference to the following detailed description of the illustrative embodiments read in conjunction with the accompanying drawings which form a part of this specification, and in which corresponding numerals indicate corresponding parts.

In the Drawings:

FIG. **1** is a block diagram representation of the microprocessor controlled rotating-cylinder viscometer of the present invention;

FIG. **2** is a circuit diagram of the phase locked loop controller of the present invention that controls the rate of rotation of the outer cylinder;

FIG. **3** is a circuit diagram of various blocks illustrated in FIG. **1** including the inner cylinder position indicating means, the I/O function decoder and the keyboard entry to the microprocessor;

FIG. **4** is a tabular listing of the program memory allocation for microprocessor **10** of the present invention; and

FIGS. **5–16** are software flow diagrams for the various routines for the programmed microprocessor **10**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS OF THE PRESENT INVENTION

Referring to the figures and first to FIG. **1**, a block diagram of the rotational concentric cylinder viscometer of the present invention is shown. A microprocessor **10** functions to control the operations of the rotating viscometer, and to measure the resulting angular rotation of the inner cylinder indicative of the shear stress of the fluid at a given shear rate. The various elements of the viscometer are connected to the microprocessor **10** by way of three data buses, I/O ports **P1 (P10-P17)** and **P2 (P20-P27)**, and data bus **BUS**. In the preferred embodiment of the present invention, microprocessor **10** is manufactured and sold by Intel Corporation as its MCS 8749 Microcomputer.

A crystal controlled system clock **20** is provided to generate various frequencies used to control the functions and timing of the viscometer. In the preferred embodiment, system clock **20** outputs seven frequencies illustrated in the following Table 1:

TABLE 1

F	Frequency (Hz)
1	4,194,304
2	2,097,152
3	16,384
4	512
5	4
6	2
7	1

Frequency f1 is supplied to the microprocessor **20** for its internal timing, f2 is supplied to the programmable keyboard/display interface **72** (FIG. **3**), f3 is supplied to the keyboard encode chip **82** (FIG. **3**), f4 is supplied to the motor speed control **28**, f5 is supplied to the microprocessor **10** for digit display purposes, f6 is supplied to the motor speed indicator **24** and f7 is supplied to the elapsed timer contained in microprocessor **10**.

Command control data is outputted by the microprocessor **10** to initiate various sequencies in the elements of the viscometer or to cause data to be applied to the data buses. Operation of the microprocessor controlled viscometer is initiated from a keyboard assembly **12** having 18 buttons. Two of the 18 buttons are used to switch the power on and off to the circuits. The remaining 16 keys are labeled as follows: 10 of the keys contain the digits **0–9**, one each of the remaining 6 keys are respectively labeled STORE, RECALL, ERASE, ENTER, AUTO, and GEL. The 10 keys marked with digits **0–9** are used to input numeric data to select the speed for the various shear rates, and to select the memory locations in conjunction with the "STORE" key. The "RECALL" key is used in conjunction with a series of numeric actuated keys to display a stored value. Any speed selected and inputted to the microprocessor **20** from the keyboard and not ENTERed can be erased with the "ERASE" without interfering with the previous selected speed. Automatic programs can be terminated by actuating the "ERASE" key. The functions performed by the "ERASE" key are as follows: It clears entries during a keyboard input sequence; it clears any "Err" messages; it causes an exit from the "GEL" routine while counting elapsed time; it causes an exit from the "GEL" routine during the 20-sec comparison interval; it causes an exit from the "AUTO" sequence during settling time after speed change; it causes an exit from "RECALL"; it causes an exit from "STORE" with no effect on memory contents; it causes an exit during the 10 second mixing interval; and it causes a jump to the calibration routine if depressed during power-up.

All selected speeds have to be entered with the "ENTER" key. The functions of the "ENTER" key are as follows: It loads the keyboard input data into the programmable divider **26**; it starts the comparison routine in "GEL" at the displayed elapsed time; and it causes a return to the main program after completion of the calibration routine. All keyboard actuated numbers are displayed, with the keyboard indicator light on, until it is entered into memory. At that time, the display **16** will indicate the actual speed of the rotating outer cylinder and the resulting steady state shear stress. Any invalid number inputted will display an error "Err". The function of the "AUTO" and the "GEL" keys, will be described in detail below.

The viscometer of the present invention may be operated either in an automatic or a manual mode. In the automatic mode, "AUTO", the steady state shear stress for each of a predetermined number of preselected shear rates will be obtained and stored in memory. This data can then be used to obtain a piece-wise linear approximation to the viscosity profile of the fluid at various shear rates. In order to perform the automatic determination of the shear stress, the keyboard **12** key labeled "AUTO" must be depressed.

When the viscometer is operated in a manual mode, it is possible to preselect the speed at which the outer cylinder is to be rotated by inserting the desired rotation rate via the numbered keys and depressing the "ENTER" key. The outer cylinder will begin to rotate at the inputted speed. When the operator is satisfied that the steady state value of the shear stress has been attained, depressing the "STORE" button and a numeric button corresponding to a memory location will cause the microprocessor **10** to read both the actual speed of the outer cylinder, via motor speed indicator **24**, and the resulting shear stress. This data will be stored in the memory location corresponding to the numeric key depressed after the "STORE" key. During the manual mode of operation, the measured speed and shear stress data are outputted to two 3-digit displays **16**.

Still referring to FIG. **1**, control of the rotation of the outer cylinder **36** is achieved through the combination of microprocessor **10**, programmable divide-by-N counter **26**, motor speed control **28** and the DC-motor **30**. In particular, the pre-selected or manually entered shear rate data is outputted by microprocessor **10** as a divide factor N to programmable divide counter **26**. Counter **26** divides a feedback frequency signal **5** outputted by an optical incremental encoder **32** that is coupled to the rotation of motor **30**. The rate of rotation of motor **30** controls the frequency of the feedback frequency signal **5** that is inputted both to the programmable divide counter **26** and to the motor speed indicator **24**. The function of motor speed indicator **24** is to produce a digital code word that indicates the actual rotational speed of the motor that is occurring. The output of motor speed indicator **24** is applied as data input to the microprocessor **10**, and is read under control of the micro processor.

The output of programmable divide-by-N counter **26** is applied to motor speed control **28** where it is compared with a reference frequency supplied by system clock **20**. For the presently preferred embodiment the reference clock signal is f4, 512 Hz. The phase difference between the reference frequency and the output of the programmable counters **26** is a phase error signal that is filtered and amplified to produce the excitation signal to DC-motor **30**. Rotation of the output shaft of motor **30** is reflected as a feedback frequency signal **5**. When the feedback frequency signal **5** reaches the proper frequency, as determined by the divide factor N and the reference frequency from system clock **20**, the excitation signal to DC-motor **30** will remain constant to cause motor **30** to run at the desired velocity. Variations of the motor **30** speed will be reflected as a variation in the feedback frequency signal **5**. These variations will produce an appropriate change in the motor excitation signal to bring the motor speed back to the desired setting.

In the presently preferred embodiment of the invention, the DC-motor **30** is a permanent magnet DC-motor having an armature wound on a hollow non-magnetic core. Motors such as these having no magnetic material in the armature or rotor are known as "Ironless motors." A suitable motor of the ironless type is manufactured and sold by Interelectric Corporation of Switzerland as a Maxom DC-motor series 2332 and by Dr. Faulhaber Company of Germany as series 3557. An ironless motor is desirable because of its low inertia and fast acceleration. These features enable the motor to achieve a fast reacting precision motor control, and a short settling time.

Referring now to FIGS. **1** and **2**, the concentric rotating cylinders **36** respond to rotation of the DC-motor **30** to produce a corresponding rotation in the shaft of the inner cylinder. This angular rotation is monitored by absolute value shaft encoder **38** that outputs a digital code word indicative of the actual angular position of the inner cylinder. This digital data is inputted to a code converter **34** whose output is coupled onto one of the microprocessor **10** data buses, **P10–P17**. In the presently preferred embodiment, absolute value shaft encoder **38** outputs a 9-bit Gray code where only one bit line is permitted to change per interval of angular rotation of the encoder shaft. The position encoder **38** is graduated from −9° to +350° deflection. The code converter **34** converts the Gray code of encoder **38** into its BCD equivalent values. Code converter **34** consists of a ROM having the BCD equivalent codes stored in memory locations that are addressed by the output code words from the encoder **38**. Each output code word from encoder **30** serves as a unique address to the code converting ROM.

To perform the code conversion, a 9-bit address to the code converting ROM contained in converter **34** is generated by the encoder **38**. The most significant bit of the 10-bit address to the ROM is inputted from the microprocessor **10** on the **P23** data bus line. Under program control, microprocessor **10** causes I/O decoder **80** to generate the strobe D to multiplex onto data bus lines **P10–P17** two BCD digits of the three BCD digits that represent the angle of the inner cylinder's shaft. Data bus P23 is then set and strobe D generated to output from the code converting ROM the third BCD digit along with the + or − sign for the angle. The encoder disk **35** of encoder **38** is properly etched to produce the Gray code. To produce the electrical signals to read the etched disk **35**, the present invention uses a Texas Instruments light emitting diode array **T1L** 49 and a photosensitive transistor array T1L629.

Turning now to FIG. **2**, the motor speed indicator **24**, programmable divider counters **26** and motor speed control **28** are illustrated in more detail. The encoder **32** consists of a rotatable disc **40** having slits or means therein for permitting the passage of light from light emitting diode D1 to reach the base of light sensitive transistor **Q1**. The output of transistor **Q1** is amplified and applied to comparator **A1** to produce a digital signal at the input of exclusive OR gates **44**. The output of exclusive OR gates **44** comprises the feedback frequency signal **5**. For the preferred embodiment, encoder **32** produces 3840 pulses per revolution on the output shaft of outer cylinder **36**. At a rotor speed of 600 RPM, encoder **32** produces a frequency of 76,800 pulses per second.

As previously discussed, the feedback frequency signal **5** is applied to programmable divider **26** to produce the phase frequency signal on its output. This signal is applied as one input to two input NAND gate **60**. Inverter **58** responds to a control signal from data bus **P25** to provide the other input to NAND gate **60**. Control signal **P25** functions to select the phase frequency clock from programmable divider **26** as the input signal to phase detector **68** for all rotor speeds above 1 RPM. When a rotor speeds of 1 RPM is desired, the microprocessor **10** outputs a control signal on **P25** to select the feedback frequency signal **5** as the frequency to be applied directly to phase detector **68** by way of NAND gates **62** and **64**.

As illustrated in FIG. **2**, NAND gates **58**, **60**, **62** and **64** function as an AND/OR gate to select either the output of the programmable divider **26** or the feedback frequency signal **5** as the input clock signal to phase detector **68** depending upon the state of data bus line **P25**. The divide parameter N from the divide-by-N counter **26** is supplied to the programmable divider **26** from the microprocessor **10** BUS. Programmable divider **26** is manufactured and sold by Intel Corporation as a model 8253 divide-by-N counter. Prescaler counter **52** which forms part of the motor speed indicator **24** is contained in the Intel 8253 chip.

Also inputted to the motor speed control circuit **28** is a second control signal, **P27**, from microprocessor **10**. This signal enables the phase detector **68** to generate an excitation signal to the motor **30** to cause it to begin rotation. When data bus line **P27** is not active, motor **30** will not rotate. When enabled by **P27**, the 512 Hz frequency signal f4 from the system clock **20** is applied to phase detector **68** which, for the preferred embodiment of the present invention, is manufactured and sold by Motorola Incorporated as a phase/frequency detector MC14568. This particular phase detector contains a divide by 4 internal counter to reduce the 512 Hz reference signal down to 128 Hz. The phase detector **68** produces an error signal representative of the phase difference between the signal from the encoder **32** divided by the division ratio N, and the 128 Hz reference signal. This error signal is filtered and amplified by amplifier A2 and power amplifier Q3 to provide the excitation signal to the motor. It should be clear that the values of the various circuit components, voltages, and their manufacturer type numbers depicted in FIG. **2** and described above will vary depending upon the intended use. In a presently preferred embodiment use in connection with a phase locked loop control system to control the speed of rotation of motor **30**, Table 2 below sets out exemplary values which have been found satisfactory.

TABLE 2

REFERENCE	VALUE (ohms)	REFERENCE	TYPE or VALUE
R1	120	C1	820pf
R2	1K,VAR	C2,C6	.1 f
R3	47K	C3,C7	.001 f
R4,R6,R12	100K	C4	1 f
R5,R9	1K	C5	10 f
		D1	OPTRON INC. 81355
R7, R13	100K,VAR	D2	55T
R8	330K	Q1	OPTRON INC. 81355
R10, R11	10K	Q2	2N4123
R14	6.8K	Q3	MJE6044, 2N6388
R15	39	A1	LM311, MLM311 (National)
		A2	LM358, MLM358 (Motorola)

Still referring to FIG. **2**, the motor speed indicator **24** for determining the actual speed of rotation of the motor **30** is shown. The feedback frequency signal **5** is applied to a divide by 64 pre-scaler **52** to reduce the frequency generated by encoder **32**. This reduced frequency is applied to a 3-digit BCD counter **54** that is periodically cleared by the 2 Hz reference signal f6 from the system clock **20**. Counter **54** is manufactured and sold by Motorola as model MC14553. The 3-digit counter **54** functions to generate a 3-digit BCD code equal to the number of pulses produced in a time interval of one second, and multiplexes each digit sequentially onto its output. The multiplexed output of the 3-digit counter **54** is applied to a tri-state buffer circuit **56** that responds to function strobe A from decoder **22** to apply the BCD digits onto the microprocessor bus **P10–P16**. Also strobed onto the data bus lines **P10–P16** are the digit selection bits that indicate which of the three BCD digits from counter **54** is currently being multiplexed into the buffer **56**. For the presently preferred embodiment, buffer **56** is a Texas Instruments tri-state buffer model SN74LS244. The control signal A is generated in response to function control data outputted by microprocessor **10** when a reading of the speed of rotation of the outer cylinder **36** is desired.

Turning now to FIG. **3** in which various functions illustrated in FIG. **1** are illustrated in more particular detail, the absolute value shaft encoder **38** is shown responding to the rotatable inner cylinder **37** of the concentric rotating cylinders. The encoder **38** functions in a similar manner to the optical encoder **32** in that light emitting diodes D3–D11 are used to produce light that is applied to the bases of transistors Q4–Q12 through a disc that rotates with the shaft of the inner cylinder **37**. Each output of transistors Q4–Q12 is applied to a respective buffer gate **70** to produce the 9-bit digital code representative of the angular position of the inner cylinder **37**. As previously mentioned, the 9-bit Gray code word is applied to code converter **34** for conversion to BCD digits that are applied to the microprocessor data bus lines P10–P17. The data from the encoder **38** is applied to the bus through the code converter **34** in response to function strobe D outputted by the I/O function decoder **22**.

The I/O function decoder chip **22** which generates the various function strobe signals is of a 1-of-8 decoder that responds to the microprocessor **10** data bus lines P20–P22 to produce eight strobes used to control various sequencies and to enable data to be inputted to the microprocessor **10** data buses. For the preferred embodiment, decoder **22** is manufactured and sold by Intel Corporation as model 8205. Also illustrated in FIG. **3** is the system clock **20**. It will be appreciated by those of ordinary skill in the art that the basic reference frequency produced by a crystal controlled oscillator may be divided down by counters to produce the reference frequencies illustrated. Accordingly, the circuits for this function are not shown and discussed herein.

Further illustrated in FIG. **3** is the keyboard **12** consisting of 16 keys that are used to input the data to the microprocessor **10** needed to operate the viscometer. The output from the various keys are applied to the keyboard encoder **82**. Encoder **82** responds to the the 16 KHz reference frequency f3 from the system clock **20** to produce the 4-bit binary code eventually applied through the buffer gates **84** to the microprocessor 10 input data bus lines P10–P13. Function strobe B enables gate **84** to apply the 4-bit code words onto the data lines. Also produced in the keyboard encoder **82** is a strobe signal that is applied to the display interface **72** which generates an interrupt request signal to microprocessor **10**. The strobe signal is only produced when one of the numeric keys is depressed. The actuation of one of the mode control keys to the microprocessor **10** does not produce an immediate response from the microprocessor. Rather, the internal software routines will periodically read the output from the keyboard buffer gates **84** and determine if any of the function keys have been depressed.

Still referring to FIG. **3**, the two 3-digit displays **16** are shown diagrammatically as composed of 7-segment display digits **74** that respond to digital driver **76** and display interface **72**. The digits to be displayed in the digits **74** are loaded from the microprocessor **10** BUS lines into the display interface **72** on the occurrence of the control signal E from the I/O function decoder **22**. The various digits to be displayed are serially loaded into display interface **72** which time multiplexes the digits onto the control lines to the digits of display **74**. In this manner, the data stored in display interface **72** appears to be continuously displayed by the display unit **74**. The presently preferred embodiment has used an Intel Corporation 8279 display chip for display **16**.

As previously mentioned, the present invention is able to determine the steady state value for the shear stress at each of the preselected rotor speeds. Shortly after application of power to the electronic circuits, the microprocessor **10** measures the angular position of the inner cylinder at zero speed to determine if an offset error is present. This offset error is used to correct all further angular position measurements. Upon entry into the automatic mode by microprocessor **10**, the outer cylinder is rotated at 700 RPM for a period of 10 seconds to mix the fluid. Mixing is required to cause a breakdown of all particle bonds for particles suspended in the fluid. At the end of the 10 second interval, the outer cylinder is then rotated at 600 RPM a period of 2 seconds to allow for the speed of the outer cylinder **36** to stabilize and become phase locked to the fixed reference signal from the system clock **20**. Readings of the angular deflection as reflected from absolute value shaft encoder **38** are then taken at a sample rate of 128 samples/second for one second.

Characteristic of all concentric rotating cylinder viscometers is the presence of fluctuations in the angular position of the inner cylinder **37** due to random variations in the torque transmitted by the fluid to the inner cylinder **37**. The magnitude and rate of the fluctuations may vary from fluid sample to fluid sample depending on the amount and size of the solid particles present. For the present invention, it is important that the sample rate of angular position readings of the inner cylinder **37** be at least two times the maximum rate of fluctuations present in the angular position of the inner cylinder. As the readings are taken, they are consecutively totalized until all of the readings have been taken. Then, the total is divided by the number of samples taken, **128**, to give an average angular deflection of the inner cylinder position for that one second measuring interval. The presence of solid particles in the fluid being tested can exert intermittent or irregular forces on the cylinder thus causing the cylinder to oscillate about a mean angular position. The averaging sequence eliminates the need for a mental averaging by the operator to obtain this mean, and thereby reduces the possibility of an error in the reading.

Many fluids exhibit thixotropic properties and require a certain time period for particle bonds to reform after a reduction in shear rate. After all bonds that can exist at a particular shear rate have reformed, the shear stress will reach an equilibrium value and a reading may be taken. For this reason, the averaging sequence is performed again after a two second time interval. The next average value thus obtained is compared to the previous average value, and if the two valves are within plus or minus one degree ($\pm 1°$) of each other, the current average value is accepted as the true equilibrium or steady state reading. If the current average value differs in magnitude by more than one degree from the previous average value, another two second time interval elapses and the averaging process is again repeated. This procedure continues until the difference between the present and previous readings are within the desired range.

After the steady state reading has been determined, that reading, along with the shear rate at which it was obtained, is stored in a memory location for later recall and display. In one embodiment of the present invention, the rotational speeds of 600, 300, 200, 100, 60, 30, 15, 6 and 3 RPMs are recommended to obtain shear stress readings that will permit the piece-wise linear approximation of the shear stress versus shear rate curve, and allow the operator to make calculations on certain rheometric properties of the fluid. The various shear rates to obtain the shear stress profile would have been inputted into the microprocessor **10** prior to initiating the automatic mode of operation. The above described procedure for obtaining the steady state shear stress at a shear rate would then be repeated for each of the preselected and inputted shear rates until the measurements of shear stress at each of the speeds has been obtained.

In the automatic mode, after all of the preprogrammed shear rate readings have been measured and recorded, the microprocessor **10** proceeds to the GEL mode. This GEL mode is also separately selectable by the operator by depressing the button on the keyboard marked "GEL." Upon initial entry into the GEL mode, the outer cylinder **36** is rotated at 700 RPM for a period of 10 seconds. Again to mix the fluid under test and to break down particle bonds that give the fluid thixotropic properties. After the mixing period, the outer cylinder rotation is stopped and the elapsed time counter interval to microprocessor **10** is initiated to generate the elapsed time. The microprocessor **10** internal elapse time counter is incremented once every second by f7, and upon reaching 10 seconds, the outer cylinder **36** is rotated at 3 RPM. Immediately as the outer cylinder **36** starts to rotate at 3 RPM, readings of the angular displacement of the inner cylinder **37** are taken in rapid succession for a period of 20 seconds corresponding to one complete revolution of the outer cylinder **36**. During this 20 second time period, the largest value is retained, and after the 20 second period, this maximum value is stored in an operator specified addressable memory location for later recall. This stored reading corresponds to the inital GEL strength of the fluid under test. The fluid is then mixed as before and then the same sequence of measurements occur after a second time period of 10 minutes. The elapse timer can be interrupted manually by depressing the ENTER button and with this manual override, any time GEL, up to 600 seconds can be taken. When all measurements are completed, the microprocessor **10** exits the GEL routine and leaves the outer cylinder rotating at 3 RPM with the display showing the speed and corresponding shear stress reading.

Referring now to FIGS. **5–16**, software flow diagrams for various functions performed by the present invention are shown. These flow diagrams illustrate the functions performed by microprocessor **10** in response to the various modes of operation keyed from keyboard **12**. The following is an assembler language listing of the microprocessor **10** program that implements the flow diagrams of FIGS. **5–16**. It will be appreciated by those skilled in the art that other routines other than those illustrated and described herein could be programmed into microprocessor **10** and achieve the same results.

```
TITLE( 8749 2K RHEOMETER PROGRAM V2
MACROFILE   DEBUG XREF PAGEWIDTH (80) NOGEN
WRITE       MACRO PORT2,DBUS
            MOV A, #PORT2
            OUTL P2,A
            MOV A, #DBUS
            OUTL BUS,A
            ENDM
PREP        MACRO AND,OR,PORT
            ANL P2,#AND
            ORL P2,#OR
            MOV A,#PORT
            OUTL BUS,A
            ENDM
TAB7        EQU 0ECH
            MOV A,#0GH          ;RESET 8279
            OUTL P2,A
            NOP
            ANL P2,#00H
            MOV RO,#18H         ;CLEAR RAM 18 to 7F
            MOV R7,#68H
            CLR A
CLEAR:      MOV @RO,A
            INC R0
            DJNZ R7,CLEAR
            WRITE 15H, 06H      ;SET KYDB/DISP MODE
            MOV A,#35H
            OUTL BUS,A          ;PROGRAM 8279 CLOCK
            MOV A,#0C3H
            OUTL BUS,A          ;CLEAR ALL IN 8279
            MOVA,#80H
            MOV T,A
            STRT T
            JTF +4
            JMP -2
            STOP TCNT
            WRITE 1BH, 16H      ;PROGRAM 8253 CNT 0
            MOV A,#56H
            OUTL BUS,A          ;PROGRAM 8253 CNT 1
            MOV A,#0B5H
            OUTL BUS,A          ;PROGRAM 8253 CNT 2
            WRITE 0BH,40H       ;LOAD CNT 1
            WRITE 13H,00H
            MOV A,#01H
```

-continued

```
          OUTL BUS,A
          MOV A,#02H
          OUTL P2,A          ;SET FOR KYBD INPUT
          JMP OFFADJ
KYBD:     ANL P2,#0A0H
          ORL P2,#02H
          JNI FUNC
          MOV R7,#04H
STAT:     JNI DATIN
          MOV R0,#18H
          ANL P2,#0E0H
          ORL P2,#42H
          IN A,P1            ;INPUT KYBD DATA
          ANL A,#0FH
          XCH A,@RO
          INC R0
          XCH A,@RO
          INC R0
          MOV @RO,A
          MOV R0,#18H
          MOV R1,#1BH
          MOV R6,#03H
          MOV A,@RO
          MOV @R1,A
          INC R0
          INC R1
          DJNZ R6,$-4
          CALL DISP
          CALL CLRFIF
          DJNZ R7,STAT
          JMP ERROR
DATIN:    ANL P2,#0E0H
          ORL P2,#02H
          IN A,P1
          ANL A,#0FH
          MOV R5,A
          XRL A.#0AH
          JZ ERASE           ;TEST FOR 'ERASE'
          MOV A,R5
          XRL A,#0BH
          JZ ENTIN           ;TEST FOR 'ENTER'
          JMP STAT
ERASE:    CLR A
          MOV R0,#18H
          MOV R7,#06H
          MOV @RO,A
          INC R0
          DJNZ R7,$-2
          JMP KEYOUT
ERROR:    MOV R0,#1BH        ;LOAD 'ERR' MESSAGE
          IMP (13H, 13H)
          MOV @RO, #M
          INC R0
          ENDM
          MOV @RO,#0FH
          CALL DISP
          ANL P2,#0E0H
          ORL P2,#02H
          IN A,P1
          ANL A,#0FH
          XRL A,#0AH
          JZ ERASE           ;TEST FOR 'ERASE'
          JMP $-7
ENTIN:    MOV R0,#1AH        ;TOTAL KYDB REGISTER
          MOV A,@RO
          DEC R0
          ADD A,@R0
          MOV R7,A
          DEC R0
          ADD A,@R0
          JZ MOTOFF
          DEC A
          JNZ G0ENT
          MOV A,R7
          JNZ GOENT
          MOV a,#0A0H
          OUTL P2,A
          MOV R0,#18H
          CLR A
          MOV @R0,A
          INC R0
          MOV @R0,A
```

-continued

```
        INC R0
        MOV @R0,A
        JMP KEYOUT
MOTOFF: CLR A              ;TURN MOTOR OFF
        OUTL P2,A
        JMP KEYOUT
GOENT:  CALL ENTER
        JMP KEYOUT
FUNC:   IN A,P1            ;CHECK KYBD FUNCTIONS
        ANL A,#0FH
        MOV R5,A
        XRL A,#0CH
        JNZ $+4
        JMP GEL
        MOV A,R5
        XRL A,#0DH
        JNZ $+4
        JMP AUTO
        MOV A,R5
        XRL,#0EH
        JNZ $+4
        JMP RECALL
        MOV A,R5
        XRL A,#0FH
        JNZ $+4
        JMP STORE
        JMP KEYOUT
GEL:    CALL GMESS
        CALL MIX
        MOV R4,#0F6H       ;R4=CNT START CODE
        MOV R5,#26H        ;R5=STORAGE ADDRESS M
        MOV R6,#01H        ;R6=NO. OF TF OVERFLO
        MOV R7,#00H        ;R7=100's of SEC CNTR
STOPMO: CLR A
        OUTL P2,A
        MOV A,#0FEH
        MOV T,A
        STRT CNT
        MOV A,R5
        MOV R0,A
        CLR A
        MOV @RO,A          ;CLEAR STORAGE MEMORY
        DEC R0
        MOV @RO,A
        DEC R0
        MOV @RO,A
        JTF $+4
        JMP $-2
        STOP TCNT
        CALL GMESS
COUNT:  MOV A,R4
        MOV T,A
        STRT CNT           ;START TIMER
TFTEST: JTF LOOPS
        MOV A,#02H
        OUTL P2,A
        IN A,P1
        ANL A,#0FH
        MOV R3,A
        XRL A,#0BH         ;TEST FOR 'ENTER'
        JNZ $+4
        JMP GOGEL
        MOV A,R3
        XRL A,#0AH         ;TEST FOR 'ERASE'
        JZ GELOUT
        MOV A,T
        CPL A
        ADD A,R4
        CPL A
        MOV R2,A
        MOV R1,#00H
        MOV R0,#1BH
TENS:   MOV A,R2
        CPL A              ;CONVERT TIMER VALUE
        ADD A,#0AH         ;TO 2 BCD NUMBERS
        JC ONES
        INC R1
        CPL A
        MOV R2,A
        JPM TENS
ONES:   MOV A,R2
        MOV @R0,A
```

-continued

```
               INC R0
               MOV A,R1
               MOV @R0,A
               INC TO
               MOV A,R7
               MOV @R0,A
               CALL DISP
               JMP TFTEST
LOOPS:         DEC R6
               MOV A,R6
               JZ GOGEL
               INC R7
               JMP COUNT
GOGEL:         STOP TCNT
               MOV A,#0ECH
               MOV T,A
               STRT CNT
               MOV A,R5
               ADD A,#1FH
               MOV R0,A
               MOV R1,A
               MOV @R0,#0EH        ;LOAD 'G-N' MESSAGE
               DEC R0
               MOV @R0,#0AH
               DEC R0
               MOV A,R1
               JBO $+6
               MOV @R0,#02H
               JMP $+4
               MOV @R0,#01H
               MOV R0,#18H
               MOV R3,#02H
               MOV @RO,#03H        ;LOAD 003 RPM
               INC R0
               CLR A
               MOV @R0,A
               INC R0
               MOV @R0,A
               MOV R0,#1BH
               DJNZ R3,$-9
               CALL ENTER
               CALL DISP
MAGCOM:        CALL STRESS
               MOV R0,#20H         ;PREVENT NEG READINGS
               MOV A,@R0
               XRL A,#0AH
               JZ MAGOUT
               MOV A,R5
               MOV R1,A
               MOV A,@R1
               MOV R3,A            ;R3=OLD DATA
               MOV R0,#20H
               MOV A,@R0
               MOV R2,A            ;R2=NEW DATA
               CALL COMP
               JF1 MAGOUT          ;F1=[R3 R2]
               JNZ STOMAX          ;[A=0] = [R3=R2]
               CLR C
               DEC R0
               DEC R1
               MOV A,@R1
               DEC R1
               SWAP A
               ADD A,@R1
               MOV R3,A
               MOV A,@R0
               DEC R0
               SWAP A
               ADD A,@R0
               MOV R2,A
               CALL COMP
               JF1 MAGOUT
               JNZ STOMAX
               JMP MAGOUT
STOMAX:        CALL STODAT         ;STORE NEW DATA
MAGOUT:        JTF AGAIN
               MOV A,#82H
               OUTL P2,A
               IN A,#82H
               ANL A,#0FH
               XRL A,#0AH          ;TEST FOR 'ERASE'
               JNZ MAGCOM
```

-continued

```
AGAIN:   JMP GELOUT
         MOV A,R7
         JNZ GELOUT
         CALL GMESS
         CALL MIX
         MOV R4,#9CH        ;RESET PARAMETERS
         MOV R5,#23H
         MOV R6,#06H
         JMP STOPMO
GELOUT:  STOP TCNT
         CLR F1
         JMP KEYOUT
AUTO:    CALL AUMESS
         CALL MIX
         MOV R4,#08H
         MOV R6,#0D4H       ;START OF SPEED DATA
LOAD:    MOV A,#0FEH
         MOV T,A            ;START 2 SEC TIMER
         STRT CNT
         MOV R0,#1AH
         MOV R1,#1DH
         MOV R7,#03H
         MOV A,R6
         MOVP3 A,@A         ;LOAD SPEED DATA
         MOV @R0,A
         MOV @R1,A
         DEC R0
         DEC R1
         INC R6
         DJNZ R7,$-7
         MOV A,R4
         INC A
         RL A
         ADD A,R4
         ADD A,#41H
         MOV R1,A
         MOV R0,#1BH
         MOV R7,#03H
         MOV A,@R0
         MOV @R1,A
         INC R0
         INC R1
         DJNZ R7,$-4
         CALL ENTER
         CALL AUMESS
         CALL DISP
         MOV A,#82H
         OUTL P2,A
         CLR A
         MOV R7,#04H        ;CLEAR RAM 7AH TO 7DH
         MOV R0,#7AH
         MOV @RO,A
         INC R0
         DJNZ R7,$-2
RUN:     JTF STEP
         IN A,P1            ;TEST FOR ERASE
         ANL A,#0FH
         XRL A,#0AH
         JNZ RUN
         JMP KEYOUT
STEP:    STOP TCNT
         MOV R7,#80H
         SEL RB1
         CLR A
         MOV R4,A
         MOV R5,A
         MOV R0,#20H
         SEL RB0
BCDHEX:  CALL STRESS
         MOV R0,#20H        ;PREVENT NEG READINGS
         MOV A,@R0
         XRL A,@9AH
         JNZ $+8
         CLR A
         MOV @R0,A
         DEC R0
         MOV @R0,A
         DEC R0
         MOV @R0,A
         SEL RB1
         MOV A,#0BBH
         MOV T,A
```

-continued

```
STRT T
JTF $+4
JMP $-2
STOP TCNT
CLR C
MOV A,@R0
MOV R2,A
RL A
RL A
MOV R3,A
RL A
RL A
RL A
MOV R2,A
ADD A,R3
MOV R3,A
MOV A,R2
RL A
ADD A,R3
MOV @R0,A
JNC $+4
INC R5
CLR C
MOV A,R7
RL A
MOV R3,A
RL A
RL A
ADD A,R3
MOV R7,A
ADD A,R6
ADD A,@R0
JNC $+4
INC R5
CLR C
ADD A,R4
JNC $+4
INC R5
CLR C
MOV R4,A            ;R4 CONTAINS HEX SUM
SEL RB0             ;R5 CONTAINS OVERFLOW
DJNZ R7,$+4
JMP $+4
JMP BCDHEX
SEL RB1             ;CALC AVERAGE VALUE
CLR F0
CLR C
MOV A,R5
RLC A
MOV R5,A
MOV A,R4
JB7 $+4
JMP $+5
MOV A,R5
INC A
MOV R5,A
MOV R0,#7CH         ;DETERMINE IF SYSTEM
MOV R1,#7BH         ;WAS IN EQUILIBRIUM
JNC $+6
MOV @R1,#01H
JMP $+4
MOV @R1,#00H
MOV A,@R0
XRL A,R5
JZ EQCARR
DEC R1
MOV A,R5
ADD A,#01H
JNC $+6
MOV @R1,#01H
JMP $+4
MOV @R1,#00H
XRL A,@R0
JZ EQCARR
MOV A,R5
CPL A
ADD A,#01H
CPL A
MOV R7,A
JNC $+6
MOV@R1,#00H
JMP $+6
```

-continued

```
          INC R1
          MOV A,@R1
          DEC R1
          MOV @R1,A
          MOV A,R7
          XRL A,@R0
          JZ EQCARR
UNSTAB:   MOV A,R5
          MOV @R0,A
          MOV R1,#7BH
          INC R0
          MOV A,#R1
          MOV @R0,A
          MOV A,#0FEH
          MOV T,A
          STRT CNT
          SEL RB0
          JMP RUN
EQCARR:   MOV R0,#7DH
          MOV R1,#7AH
          MOV A, @R0
          XRL A, @R1
          DEC R0
          JNZ UNSTAB
          MOV A, @R1          ;DATA ACCEPTED
          CPL A
          JB0 $+4
          CPL F0
          CLR C
          MOV R0,#20H         ;CONVERT HEX TO BCD
          MOV $7,#00H
          MOV @R0,#00H
NSD:      MOV A,R5
          CPL A
          ADD A,#0AH
          JC LSD
          INC R7
          CPL A
          MOV R5,A
          JMP NSD
LSD:      MOV A,R5
          MOV R6,A
HUNS:     MOV A,R7
          CPL A
          ADD A,#0AH
          JC ADD256
          INC@R0
          CPL A
          MOV R7,A
          JMP HUNS
ADD256:   JF0 $+4
          JMP AVOUT
          MOV A, R6
          ADD A,#06H
          MOV R6,A
          MOVA,R7
          ADD A,#05H
          MOVR7,A
          MOV A, @R0
          ADD A, #02H
          MOV @R0,A
          MOV A,R6
          ADD A,#0F6H
          JNC $+5
          INC R7
          MOV R6,A
          CLR C
          MOV A,R7
          ADD A,#0F6H
          JNC $+5
          MOV R7,A
          INC @R0
          CLR C
AVOUT:    SEL RB0
          MOV A,R4
          INC A
          RL A
          ADD A,R4
          ADD A,#24H
          MOV R1,A            ;STORE STRESS READING
          MOV R0,#20H
          MOV R7, #03H
```

-continued

```
                MOV A,@R0
                MOV @R1,A
                DEC R0
                DEC R1
                DJNZ R7,$-4
                DJNZ R4,$+4
                JMP GEL
                JMP LOAD
RECALL:         ANL P2,#0A0H
                ORL P2,#02H
                MOV A,#0FBH
                MOV T,A
                STRT CNT          ;START 5 SEC. TIMER
                JTF $+9
                IN A,P1
                ANL A,#0FH
                XRL A,#0AH
                JNZ $+4
                JMP KEYOUT
                JNI $-11
                IN A,P1           ;READ MEMORY LOCATION
                ANL A,#0FH
                MOV R4,A
                RL A
                ADD A,R4
                MOV R4,A
                ADD A,#21H
                MOV R1,A
                MOV R0,#1EH       ;LOAD STRESS DATA
                MOV R7,#03H
                MOV A,@R1
                MOV@R0,A
                INC R0
                INC R1
                DJNZ R7,$-4
                MOV A,R4          ;CALCULATE RPM ADDRESS
                ADD A,#40H
                MOV R1,A
                MOV R0,190 1BH
                MOV R7,#03H
                MOV A,@R1
                MOV @R0,A
                INC R0
                INC R1
                DJNZ R7,$-4
                CALL DISP
                CALL CLRFIF
                JMP RECALL
STORE:          IN A,P1
                ANL A,#0FH
                MOV R5,A
                XRL A,#0AH
                JNZ $+4
                JMP KEYOUT
                JNI STORE
                MOV A,R5          ;CALC STRESS ADDRESS
                RL A
                ADD A,R5
                MOV R4,A
                ADD A,#23H
                MOV R5,A          ;CALCULATE RPM ADDRESS
                MOV A,R4
                ADD A,#40H
                MOV R4,A
                CALL STODATE      ;STORE STRESS DATA
                MOV A,R4
                MOV R1,A
                MOV R0,#1BH       ;STORE RPM DATA
                MOV R3,#03H
                MOV A,@R0
                MOV @R1, A
                INC R0
                INC R1
                DJNZ R3,$-4
                CALL CLRFIF       ;CLEAR FIFO OF 8279
                JMP KEYOUT
KEYOUT:         STOP TCNT
                JTO $+4
                JMP $+13
                JF1 $+9
                CALL RPM
                CALL STRESS
```

-continued

```
         CALL DISP
         CPL F1
         JMP KYBD
         CLR F1
         JMP KYBD
         ORG 400H
OFFADJ:  MOV R0,#7FH
         CLR A
         MOV R3,A
         MOV @R0,A
         MOV A,#0FEH
         MOV T,A
         STRT CNT            ;START 2 SEC. TIMER
         JTF $+4
         JMP $-2
         STOP TCNT
CAL:     ANL P2,#0A0H
         ORL P2,#02H
         IN A,P1
         ANL A,#0FH
         XRL A,@0AH
         JNZ ADJUST
         CALL STRESS
         CALL DISP
         JMP CAL
ADJUST:  MOV A,#0FEH
         MOV T,A
         STRT CNT            ;START 2 SCE. TIMER
         JIF $+4
         JMP $-2
         STOP TCNT
         ANL P2,#0A0H
         ORL P2,#04H
         IN A,P1             ;READ OFFSET
         MOV R2,A
         ORL P2,#08H
         IN A,P1
         ANL A,#0FH
         MOV R0,@7EH
         MOV @R0,A
         CALL COMP
         JZ $+6
         MOV A,R2
         MOV R3,A
         JMP ADJUST
         MOV R1,#7FH
         MOV A,@R0
         JNZ $+6
         MOV A,R2
         MOV @R1,A
         JMP $+6
         MOV A,R2
         ADD A,#80H
         MOV @R1,A
         CLR C
         CLR F1
         JMP KYBD
DISP:    PREP 0F0H, 15H,90H
         ANL P2,#0EFH        ;SET C/D LOW
         MOV R0,#1BH
         MOV R2,#06H
EACH:    MOV A,@P0
         ADD A,#TAB7
         MOVP3 A,@A
         OUTL BUS,A
         INC R0
         DJNZ R2,$+3
         RETR
         JMP EACH
STRESS:  ANL P2,#0A0H
         ORL P2,#04H
         MOV R0,#20H
         IN A,P1             ;READ LSD AND NSD
         MOV R1,A
         ORL P2,#08H         ;SET A9 HIGH
         NOP
         IN A,P1             ;READ MSD
         ANL A,#0FH
         MOV @R0,A
         DEC R0
         MOV A,R1
         SWAP A
```

-continued

```
                ANL A,#0FH
                MOV @R0,A           ;LOAD DATA TO REGISTER
                DEC R0
                MOV A,R1
                ANL A,#0FH
                MOV @R0,A
                CLR C
                MOV R0,#20H
                MOV $1,#03H
                MOV A,@R0
                ADD A,@0F5H
                JNC 4+4
                JMP STRESS
                DEC R0
                DJNZ R1,$-8
                MOV R0,#7EH
                MOV R1,#7FH
                MOV A,@R1
                MOV @R0,A
NEWOFF:         MOV R0,#7EH
                MOV A,@R0
                MOV R1,A
                JNZ $+4
                JMP ADJOUT
                JB7 NEGOFF
                MOV R0,#20H
                MOV A,@R0
                XRL A,#0AH
                JZ ADDN
                MOV R0,#1EH
                MOV A,@R0
                JZ $+8
                DEC A
                MOV @R0,A
CNTR:           DJNZ R1,$-7
                JMP ADJOUT
                INC R0
                MOV A,@R0
                JZ $+9
                DEC A
                MOV @R0,A
                DEC R0
                MOV @RO,#09H
                JMP CNTR
                MOV R0,#20H
                MOV A,@R0
                JZ $+12
                DEC A
                MOV @R0,A
                DEC R0
                MOV @R0,#09H
                DEC R0
                MOV @R0,#09H
                JMP CNTR
                MOV @R0,#0AH
                JMP ADDN
NEGOFF:         MOV R0,#2 0H
                MOV A,@R0
                XRL A,#0AH
                JNZ CLRB7
                MOV R0,#1EH
                MOV A,@R0
                DEC A
                MOV @R0,A
                ANL A,#0FH
                MOV R1,A
                DJNZ R1,$+4
                JMP ADJOUT
                MOV R0,#7EH
                MOV A,@R0
                DEC A
                MOV @R0,A
                MOV R0,#1EH
                MOV A,@R0
                JNZ $+6
                MOV R0,#20H
                MOV @R0,#00H
                JMP NEWOFF
CLRB7:          MOV A,R1
                ANL A,#0FH
                MOV R1,A
ADDN:           MOV R0,#1EH
```

-continued

```
                MOV A,@R0
                INC A
                DA A
                NOP
                NOP
                NOP
                JB4 $+9
                MOV @R0,A
                DJNZ R1,$+4
                JMP ADJOUT
                JMP ADDN
                ANL A,#0FH
                MOV @R0,A
                INC R0
                JMP $-19
ADJOUT:         MOV R0,#1EH
                MOV A,@R0
                JNZ $+14
                INC R0
                MOV A,@R0
                JNZ $+10
                INC R0
                MOV A,@R0
                XRL A,#0AH
                JNZ $+4
                MOV @R0,#00H
                RETR
RPM:            ANL P2,#0A0H
                ORL P2,#01H
                MOV R0,#1BH
                MOV R7,#03H
                MOV R1,#10H             ;SET MASK
RPMIN:          IN A,P1
                MOV R3,A
                CPL A
                ANL A,R1
                XRL A,R1
                JNZ RPMIN
                MOV A,R3
                ANL A,#0FH
                MOV @R0,A
                INC R0
                DJNZ R7,$+3
                RETR
                MOV A,R1
                RL A                    ;ROTATE MASK
                MOV R1,A
                JMP RPMIN
COMP:           CLR F1
                CLR C
                MOV A,R2
                CPL A
                ADD A,R3
                INC A
                JNC LTEQ
                CPL F1
                JN $+3
                CLR F1
LTEQ:           RETR
ENTER:          MOV A,#93H
                OUTL P2,A
                MOV R0,#18H
                MOV A,@R0
                INC R0
                SWAP A
                ADD A,@R0
                INC R0
                SWAP A
                OUTL BUS,A
                MOV A,@R0
                OUTL BUS,A
                CLR A
                MOV @R0,A
                DEC R0
                MOV @R0,A
                DEC R0
                MOV @R0,A
                RETR
MIX:            MOV A,#0F5H
                MOV T,A
                STRT CNT                ;START 10 SEC. TIMER
                MOV R0,#1AH
```

-continued

```
                MOV R6,#0D1H
                MOV R3,#03H
                MOV A,R6
                MOVP3 A,@A
                MOV @R0,A
                DEC R0
                INC R6
                DJNZ R3,$-5
                CALL ENTER
                MOV R0,#1DH
                IRP X, 9BH,11H
                MOV @R0,#X
                DEC R0
                ENDM
                MOV @R0,#12H
                CALL DISP
                MOV A,#82H
                OUTL P2,A
                JTF $+11
                IN A,P1
                ANL A,#0FH
                XRL A,#0AH
                JZ $+4
                JMP $-9
                STOP TCNT
                RETR
STODAT:         MOV A,R5
                MOV R1,A
                MOV R0,#20H
                MOV R3,#03H
                MOV A@R0
                MOV @R1,A
                DEC R0
                DEC R1
                DJNZ R3,$-4
                RETR
GMESS:          MOV R0,#20H          ;LOAD 'GEL' MESSAGE
                IRP M, OEH,FH
                MOV @R0,#M
                DEC R0
                ENDM
                MOV @R0,#10H
                RETR
AUMESS:         MOV R0,#20H          ;LOAD 'AU' MESSAGE
                IRP M, OBH,OCH
                MOV @R0,#M
                DEC R0
                ENDM
                MOV @R0,#0DH
                RETR
CLRFIF:         PREP 0F0H,15H,0C2H
                RETR
                ORG 3D1H
                DB 07H,00H,00H,06H,00H,00H,03H,00H
                DB 00H,02H,00H,00H,01H,00H,00H,00H
                DB 06H,00H,00H,03H,00H,00H,01H,05H
                DB 00H,00H,06H,3FH,06H,5BH,4FH,66H
                DB 6DH,7DH,07H,7FH,6FH,40H,00H,77H
                DB 1CH,3DH,79H,38H,76H,06H,50H
                END
```

Although the presently preferred embodiment of the present invention has been shown and discussed herein, it will be understood that many variations and alternate embodiments of the invention will be apparent to those skilled in the art. For example, other types of optical encoders other than the Gray code encoder may be used to indicate the angular position of the BOB. Furthermore, although the viscometer has been described as being used in connection with drilling fluids in the petroleum industry, it will be understood by those skilled in the art that the invention is applicable as well in measuring rheometric properties of any type of fluid.

What is claimed is:

1. A rotating-cylinder viscometer for measuring the shear stress at a given shear rate of a fluid contained between a rotatable outer cylinder and a rotatable inner cylinder, the inner cylinder rotating in response to forces produced in the fluid by rotation of the outer cylinder, and where the amount of rotation of the inner cylinder is related to the shear stress of the fluid, the viscometer comprising:

(a) a system clock, for providing system clock signals;

(b) a microprocessor unit responsive to said system clock, for inputing and outputing data signals to select the shear rate of rotation of the outer cylinder and to obtain during measurement intervals a plurality of readings of the amount of angular rotation of the inner cylinder at each selected shear rate;

(c) a shear rate controller responsive to said clock and the shear rate selecting data from said microprocessor, for rotating the outer cylinder at a predetermined constant angular velocity;

(d) a position indicator connected to the inner cylinder for rotation therewith, for indicating the angular position of the inner cylinder;

(e) a function selector means connected to said microprocessor, for inputing to said microprocessor the mode of operation for the viscometer, and for inputing the preselected shear rates at which the outer cylinder is to be rotated; and

(f) display means responsive to said microprocessor, for displaying both a measured shear stress and the angular velocity of the outer cylinder at which the displayed shear stress was measured, said microprocessor determining from the average angular readings for the plurality of angular position readings of the inner cylinder for each measurement interval when the steady state shear stress has been reached, the steady state shear stress obtaining when the average angular readings for consecutive measurement intervals differ by no more than a predetermined amount.

2. The viscometer of claim **1** wherein the system clock is crystal controlled.

3. The viscometer of claim **1** wherein the shear rate controller comprises:

(a) a motor, for rotating the outer cylinder;

(b) a speed encoder connected to the outer cylinder for rotation therewith, said encoder outputing a feedback frequency signal;

(c) a programmable frequency divider responsive to the shear rate selecting data, for dividing the feedback frequency signal to obtain a phase detector clock signal; and

(d) a motor drive means responsive to the system clock and the phase detector clock signal, for generating the excitation signal to said motor, whereby the motor speed is controlled in accordance with the shear rate selecting data to obtain a constant frequency for the feedback frequency signal.

4. The viscometer of claim **3** wherein said speed encoder is an optical incremental encoder.

5. The viscometer of claim **3** wherein said motor drive means is enabled by said microprocessor to drive said motor, said means comprising:

(a) a phase detector responsive to a system clock signal and the phase detector clock signal, for generating a phase error signal indicative of the phase between the phase detector clock signal and the clock signal; and

(b) an amplifier, for generating the motor excitation signal from the phase error signal thereby causing said motor to rotate.

6. The viscometer of claim **3** wherein said motor is a DC-motor of the ironless armature type.

7. The viscometer of claim **3** wherein said programmable frequency divider is a divide-by-N counter.

8. The viscometer of claim **1** wherein said position indicator is an absolute value shaft encoder that outputs a code indicative of the absolute value of the shaft angle.

9. The viscometer of claim **8** wherein the code is a Gray code.

10. The viscometer of claim **9** further comprising a code converter for converting the Gray code to a BCD code.

11. The viscometer of claim **10** wherein said code converter is a read-only memory containing BCD code words that are outputted in response to memory addresses provided by the Gray code output of said absolute value shaft encoder.

12. The viscometer of claims **1** or **8** wherein the predetermined amount of angular difference between the average angular readings of consecutive measurement intervals is $\pm 1^{\circ}$.

13. The viscometer of claim **1** wherein said function selector means comprises:

(a) a keyboard having a plurality of keys including keys for generating numeric data, for generating digital code words in response to the actuation of the keys; and

(b) an interface, for interfacing the digital code words to said microprocessor, said interface generating an interrupt strobe when a numeric key is depressed.

14. A method of obtaining the shear stress of a fluid at a selected shear rate speed using a rotating-cylinder viscometer having rotatable inner and outer concentric cylinders comprising the steps of:

(a) mixing the fluid by rotating the outer cylinder at a high speed;

(b) rotating the outer cylinder at the selected shear rate speed;

(c) determining a current average value for the angular position of the inner cylinder from a predetermined number of position measurements taken at a predetermined sample rate, the angular position of the inner cylinder having random fluctuation about a position;

(d) obtaining the difference between the current average value and the last obtained average value;

(e) repeating steps (c) through (e) if the difference is greater than a predetermined number of degrees, the current average value becoming the last obtained average value for the next steady state determination; and

(f) reporting the current average value as the measured shear stress if the difference is less than the predetermined number of degrees.

15. The method of claim **14** wherein the step of mixing the fluid occurs at a speed at least as high as the selected shear rate speed at which the shear stress is to be measured.

16. The method of claim **14** wherein the predetermined sample rate is at least twice the rate of the fluctuation in the angular position of the inner cylinder.

17. The method of claim **16** wherein the predetermined number of degrees is ± 1 degree.

18. The method of claim **14** further including the steps of:

(a) determining the angular offset position of the inner cylinder at zero shear rate; and

(b) correcting all angular position measurements of the inner cylinder by the amount of the zero rate offset.

19. A method of obtaining the steady state shear stress of a fluid at a selected shear rate speed using a rotating-cylinder viscometer in which the fluid is contained between a rotatable outer cylinder and a spring loaded rotatable inner cylinder, the inner cylinder rotating in response to the torque produced by the rotation of the outer cylinder in the fluid whereby the angular rotation of the inner cylinder is indicative of the shear stress of the fluid; the method comprising the steps of:

(a) mixing the fluid by rotating the outer cylinder at a speed at least as high as the selected shear rate speed at which the shear stress is to be measured for a first predetermined interval of time;

(b) rotating the outer cylinder at the selected shear rate speed for a second predetermined interval of time;

(c) determining a current average value for the angular position of the inner cylinder from a predetermined number of position measurements taken over a third predetermined time interval;

(d) obtaining the difference between the current average value and the last obtained average value;

(e) repeating steps (b) through (e) if the difference is greater than a predetermined number of degrees, the current average value becoming the last obtained average value for the next steady state determination; and

(f) reporting the current average value as the measured shear stress if the difference is less than the predetermined number of degrees.

20. A method of obtaining the shear stress profile of a fluid for various preselected shear rate speeds using a rotating-cylinder viscometer having rotatable inner and outer concentric cylinder comprising the steps of:

(a) mixing the fluid by rotating the outer cylinder at a high speed;

(b) rotating the outer cylinder at a current shear rate speed;

(c) determining a current average value for the angular position of the inner cylinder from a position measurements taken at a predetermined sample rate, the angular position of the inner cylinder having random fluctuations about a position;

(d) obtaining the difference between the current average value and the last obtained average value, the current average value becoming the last obtained average value for the next difference determination;

(e) repeating steps (c) through (e) if the difference is greater than a predetermined number of degrees;

(f) storing the current average value as the measured shear stress if the difference is less than the predetermined number of degrees; and

(g) repeating steps (c) through (g) until the shear stress at each of the preselected shear rate speeds has been measured thereby obtaining the shear stress profile of the fluid.

21. The method of claim **20** wherein the step of mixing the fluid occurs at a speed at least as high as the highest preselected shear rate speed at which the shear stress is to be measured.

22. The method of claim **20** wherein the predetermined sample rate is at least twice the rate of the fluctuations in the angular position of the inner cylinder.

23. The method of claim **20** wherein the predetermined number of degrees is ± 1 degree.

24. The method of claim **20** further including the steps of:

(a) determining the angular offset position of the inner cylinder at zero shear rate; and

(b) correcting all angular position measurements of the inner cylinder by the amount of the zero rate offset.

25. The method of claim **23** or **24** wherein the method further includes the steps of:

(a) rotating the outer cylinder at 3 revolutions per minute;

(b) measuring the maximum shear stress reading that occurs during one revolution of the outer cylinder;

(c) repeating steps (a) and (b) after a predetermined time delay.

26. A method of obtaining a shear stress profile of a fluid for various preselected shear rate speeds using a rotating-cylinder viscometer in which the fluid is contained between a rotatable outer cylinder and a spring loaded rotatable inner cylinder, the inner cylinder rotating in response to the torque produced by the rotation of the outer cylinder in the fluid whereby the angular rotation of the inner cylinder is indicative of the shear stress of the fluid the method comprising the steps of:

(a) mixing the fluid by rotating the outer cylinder at a speed at least as high as the highest shear rate speed at which a shear stress is to be measured for a first predetermined interval of time;

(b) selecting one of the preselected shear rate speeds as the current shear rate;

(c) rotating the outer cylinder at the current shear rate speed for a second predetermined interval of time;

(d) determining a current average value for the angular position of the inner cylinder from position measurements taken at a predetermined sample rate over a third predetermined time interval, the angular position of the inner cylinder having random fluctuations about a position over a third predetermined time interval;

(e) obtaining the difference between the current average value and the last obtained average value, the current average value becoming the last obtained average value for the next difference determination;

(f) repeating steps (c) through (f) if the difference is greater than a predetermined number of degrees;

(g) storing the current average value as the measured shear stress if the difference is less than the predetermined number of degrees; and

(h) repeating steps (b) through (h) until the shear stress at each of the preselected shear rate speeds has been measured, thereby obtaining the shear stress profile of the fluid.

27. A microprocessor controlled rotating-cylinder viscometer for measuring the steady state shear stress of a fluid located between two coaxially aligned rotatable cylinders in which an outer cylinder is rotated at preselected rates and an inner cylinder is rotated from its zero rate position in response thereto, the viscometer comprising:

(a) means for rotating the outer cylinder at a constant preselected rate;

(b) a shaft encoder connected to the inner cylinder for encoding the angular position of the inner cylinder with respect to the zero rate reference position, the steady state angular position of the inner cylinder for a constant angular rate of the outer cylinder being indicative of the shear stress of the fluid located therebetween; and

(c) a programmed microprocessor unit programmed to select the shear rate of rotation of the outer cylinder, and to repetitively obtain at each rate a plurality of readings of the angular position of the inner cylinder during measurement intervals, said processor unit determining the steady state shear stress from average readings of the plurality of angular positions of the inner cylinder determined for each measurement interval, the steady state shear stress obtaining when the average angular positions of the inner cylinder between successive measurement intervals differs by no more than a predetermined value.

28. The viscometer of claim 27 wherein the predetermined value of angular difference is $\pm 1°$.

29. The viscometer of claim 27 wherein said shaft encoder is an absolute value shaft encoder for indicating the true angular position of the inner cylinder.

30. The viscometer of claim 27 wherein said rotating means comprises:

(a) a motor responsive to a driving signal, for rotating the outer cylinder;

(b) a speed encoder connected to the outer cylinder for rotation therewith, said encoder outputting a feedback frequency signal;

(c) a programmable frequency divider response to the microprocessor, for dividing the feedback frequency signal to obtain a phase detector clock signal;

(d) a phase detector responsive to said microprocessor and the phase detector signal, for generating a phase error signal indicative of the speed error between the selected shear rate and the actual rate of rotation of the outer cylinder; and

(e) an amplifier responsive to the phase error signal for generating the drive signal to said motor, whereby the motor speed is controlled in accordance with the selected shear rate from said microprocessor.

31. The viscometer of claim 30 wherein said speed encoder is an optical incremental encoder.

32. The viscometer of claims 30 or 31 wherein said motor is a DC-motor of the ironless armature type.

* * * * *